Operational Procedures of Agencies Contributing to the ISC

The Seismological Network of Aristotle University of Thessaloniki, Greece (AUTHnet)

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6

Operational Procedures of Contributing Agencies

6.1 The Seismological Network of Aristotle University of Thessaloniki, Greece (AUTHnet)

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The seismological network of Aristotle University of Thessaloniki, Greece (AUTHnet), is a permanent telemetric digital network of state-of-the-art seismological instruments, offering 24/7 seismic monitoring of Greece and its surroundings. It is maintained by the personnel of the Geophysical Laboratory of AUTH (GeoLab) to detect and record local, regional and global earthquake activity (Fig. 6.1). Following the strong ($M_w = 6.5$) earthquake of 1978 in Northern Greece, the GeoLab established its first seismological stations in Thessaloniki and neighbouring areas. After several phases of upgrades, today (October 2019) AUTHnet counts 51 seismic stations spread around the country, which are in real-time communication with the Central Seismological Station in Thessaloniki (THE-SS). The network records almost every event of magnitude M>2.0 in the broader area of Greece while a seismologist on duty analyses, statistically, about 25 regional earthquakes per day. The seismic signals are recorded, digitized, transmitted and managed using appropriate hardware and software packages.

Moreover, three local networks, connected to the main network, were developed in the last 15 years in order to monitor local seismic activity in areas of special interest (Santorini, Nisyros and Cephalonia-Lefkada islands).

AUTHnet is also a founding member of the Hellenic Unified Seismic Network (HUSN), which was formed in 2007 aiming to unify all the seismological networks of Greek Institutions and act as a wide national network.

In addition to the valuable data of AUTHnet, provided by the THE-SS to the scientific community, and the research that is carried out by its scientists, THE-SS maintains strong interaction with society

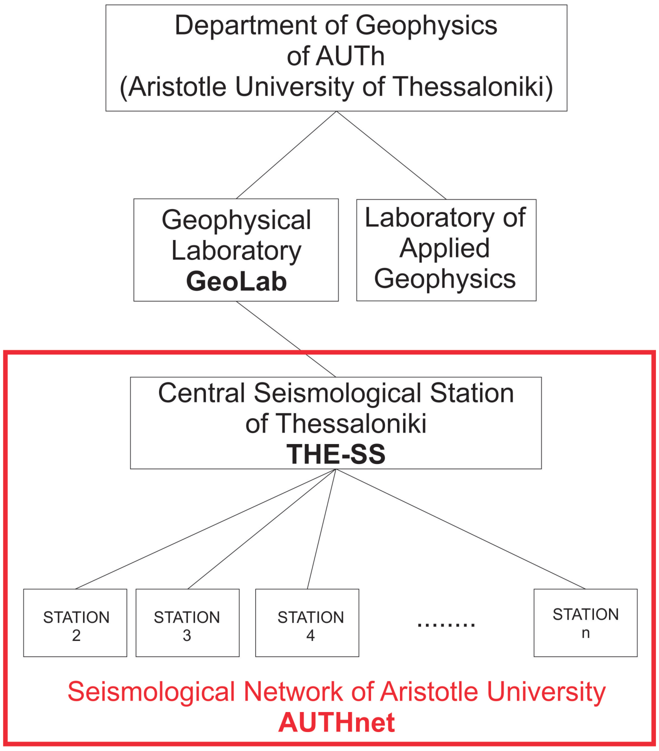

Figure 6.1: *Organisation chart of GeoLab, THE-SS and AUTHnet.*

by providing information to the authorities, the media and citizens about felt earthquakes, as well as by helping civilians to become more familiar with earthquakes and by teaching them how to be better protected.

6.1.1 Introduction

Seismic networks are necessary for scientists in order to monitor the seismic activity and to study the active tectonics of a region. Analysis of their records results in the compilation of reliable earthquake catalogues which are the basic tool for seismic hazard studies. To achieve this, records of large earthquakes as well as of smaller ones are necessary. The lower magnitude over which all earthquakes of a region will be detected and recorded by a network is an indicator of the network's detectability, strongly depending on the number of stations and on their geographical distribution.

On 20 June 1978 a strong earthquake ($M_w = 6.5$) occurred about 25 km NE of the city of Thessaloniki (*Papazachos and Papazachou*, 2003). The mainshock was preceded and followed by rich foreshock and aftershock sequences that lasted for months. This devastating earthquake was the first one in Greece to have occurred near a major city and to have had a significant impact on it. 45 people were killed, huge problems were caused in several sectors and it took months for the community to return to normal life. This earthquake triggered the installation of the seismological network of the Geophysical Laboratory of Aristotle University of Thessaloniki (AUTHnet). The network, in its first shape, was completed within 2 years and consisted of one central and 7 peripheral permanent stations located in Central Macedonia (N. Greece). On January 1st 1981, the network officially started operating. That was a big step forward for seismology in Greece and its surroundings as AUTHnet was the first telemetric seismic network supported by a mainframe computer, in the entire Balkan region.

Nowadays, (October 2019) AUTHnet consists of 51 permanent stations, covering a large part of the country. The network is registered to the International Federation of Digital Seismograph Networks (FDSN - `http://www.fdsn.org`) under the code HT, and holds the Digital Object Identifier `https://doi.org/10.7914/SN/HT`. The agency code at the ISC is THE.

6.1.2 Network Description

Time Evolution of AUTHnet

In 1979 the Central Seismological Station of Thessaloniki (THE-SS) was built at the Aristotle University of Thessaloniki and the first two seismometers, a S-13 3-component short period and a SL-220 3-component long-period, both by Teledyne-Geotech, were installed (station code THE).

By the end of 1980, the formation of AUTHnet in its initial shape was completed with the installation of seven peripheral stations at Sohos (SOH), Litochoro (LIT), Griva (GRG), Paliouri (PAIG), Kentriko (KNT), Ouranoupoli (OUR) and Serres (SRS). The region covered by the network was central Macedonia (N. Greece), with six stations on sites no more than about 100 km from Thessaloniki (Figure 6.2a).

The network expanded in several phases. The **1st phase** took place in **1989**, with four new stations installed in Igoumenitsa (IGT), Florina (FNA), Alexandroupoli (ALN) and Agios Georgios (AGG). Thus, AUTHnet expanded towards the East, West and South, at distances about 250 km from Thessaloniki, covering most of N. Greece and an area about five times larger than before. This step changed the profile of AUTHnet from a local to a regional network, significantly increasing its detectability.

While the continental part of N. Greece was well covered azimuthally, another region not far from Thessaloniki was practically out of coverage. The North Aegean Sea, an area with many catastrophic earthquakes in the last 2,500 years with continuous activity and great geotectonic interest, was the next target of AUTHnet. The **2nd phase** of the network's expansion took place in **1996**, with the installation of three new stations in Lemnos Island (LOS), Alonissos Island (AOS) and Xorichti (XOR) (Figure 6.2b).

Three years later, in **1999**, the network further expanded in western Greece **(3rd phase)**, with a new station installed on Lefkada Island (LKD), in the Ionian Sea. This is the area of the highest seismicity level not only in Greece but also in the whole central and eastern Eurasia.

During the next two years **(2000-2001)**, two more stations were installed **(4th phase)** in W. Macedonia at the areas of Kastania (KTI) and Metsovo (MEV) in order to improve the density of the network in its southwestern part.

In **2003** the first special network of GeoLab was installed in Santorini Island (south Aegean), far from the existing main network (**5th phase**, Fig. 6.2c). Santorini Island is of high scientific interest due to its famous active volcano (most recently activ in 1950). In collaboration with the Institute for the Study and Monitoring of the Santorini Volcano (I.S.MO.SA.V.), five new seismological stations were installed: THR1, THR4, THR6 on Thira Island, THR3 on Nea Kameni Island and THR5 on Thirasia Island. This local network strongly improved the detectability of AUTHnet in the S. Aegean, providing valuable data to the scientific community. In addition, it allowed continuous and detailed monitoring of the microearthquake activity of the volcano, an increase of which might be connected to possible volcano activation.

In the same year, the older S-13 analogue short period seismometers started being replaced by new digital, 3-component, broad-band sensors (CMG-3ESP, Guralp Systems).

During **2006-2008**, the **6th and 7th phase** of the AUTHnet upgrade took place in an effort to further improve the network's azimuthal coverage and its performance. A new digital station was installed very close to the city of Thessaloniki, on Mount Hortiatis (HORT), to better monitor local activity, as the THE station was situated in a populated and noisy area. AUTHnet was also expanded to the central and eastern part of Aegean Sea, on the islands of Lesvos (SIGR) and Chios (CHOS), increasing the network's sensitivity for events in the central and north Aegean Sea as well as for the NW coast of Turkey. The installation of three new stations followed, in Kavala (KAVA), Nestorio (NEST) and on Thira Island (THR2). At the same time, LKD2 in Lefkada Island replaced the older LKD station, due to technical problems.

Based on the experience gained from the local network at Santorini, a new local network was installed on the Dodecanese islands (**7th phase**, Fig. 6.2d), in order to monitor the possible microearthquake activity associated with the known volcanic center of Nisyros Island. In collaboration with the regional authorities and the recently founded Volcanic Observatory of Nisyros, a seismological station was established in 2008 (NIS1) and three more (NIS2, NIS3 and NIS4) within the next year, covering the whole island of Nisyros. However, due to many technical problems, some of these stations remained closed for long periods.

In **2010 (8th phase)**, a new station was added to the local network of Santorini in Fira (THR7). At the same time, AUTHnet was extended to the south with a new station installed in Kranidi (KRND), E. Peloponnesus. In this way, AUTHnet with more than 30 stations covering the biggest part of the country and Aegean Sea became able to detect almost all events of M>2.0 in the broader area of Greece.

Another expansion **(9th phase)** took place in **2011**, with the installation of two new stations in Kipourio (KPRO), W. Macedonia, and in Thessaly, at the Larissa Observatory (LRSO). The existing network at Santorini was enhanced with new stations in Columbo (CMBO), Athinios (THT1), Monolithos (THR8), Imerovigli (THT2), Akrotiri (THR9) and Taxiarchis (STAX). This decision was very important, as a significant seismic swarm started in January 2011, strongly related to processes showing volcanic activity inside the caldera of Santorini (*Newman et al.*, 2012). Thanks to the dense local network of AUTHnet, with more than ten operating stations in about 200 km^2, more than 1,200 earthquakes were recorded in 2011 in Santorini, most of them (about 1,000) during May-December 2011, with magnitudes M<2.5.

In **2012 (10th phase)**, another station (THAS) was installed in the N. Aegean, on the island of Thassos, increasing the sensitivity of the network in this region. To the west, in the Ionian Sea, two new stations were added on Lefkada Island, in Evgiros (EVGI) and Tsoukalades (TSLK), supporting the older LKD2. In this way, the network could better monitor the seismic activity of the area with the highest seismicity in Greece. The recent seismic activity of 2014, with two strong earthquakes (M_w=6.1 and M_w=6.0) in eight days (*Karakostas et al.*, 2015), and their rich aftershock sequence, pushed this local network to the next step. Thus, two more stations were added on Lefkada Island (in Dragano (DRAG) and Nydri (NYDR)) and another two on Cephalonia Island (in Damoulianata (DMLN) and Pessada (PSDA)). This local network was very helpful for the study of the large earthquake of Lefkada Island (M_w=6.5) some

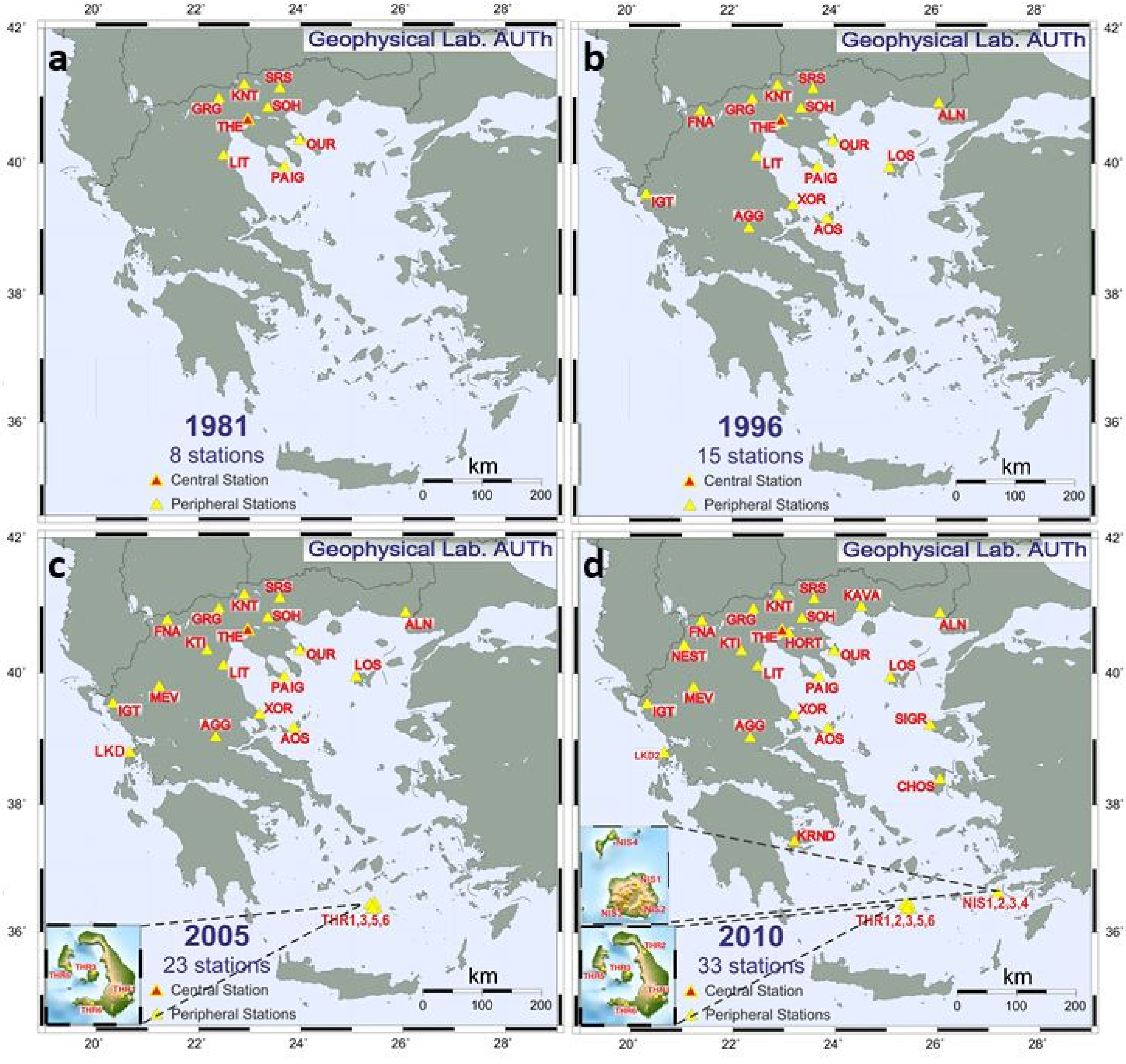

Figure 6.2: Geographical distribution of AUTHnet stations in the past including maps for the two special local networks of Santorini and Nisyros (Vamvakaris, 2018).

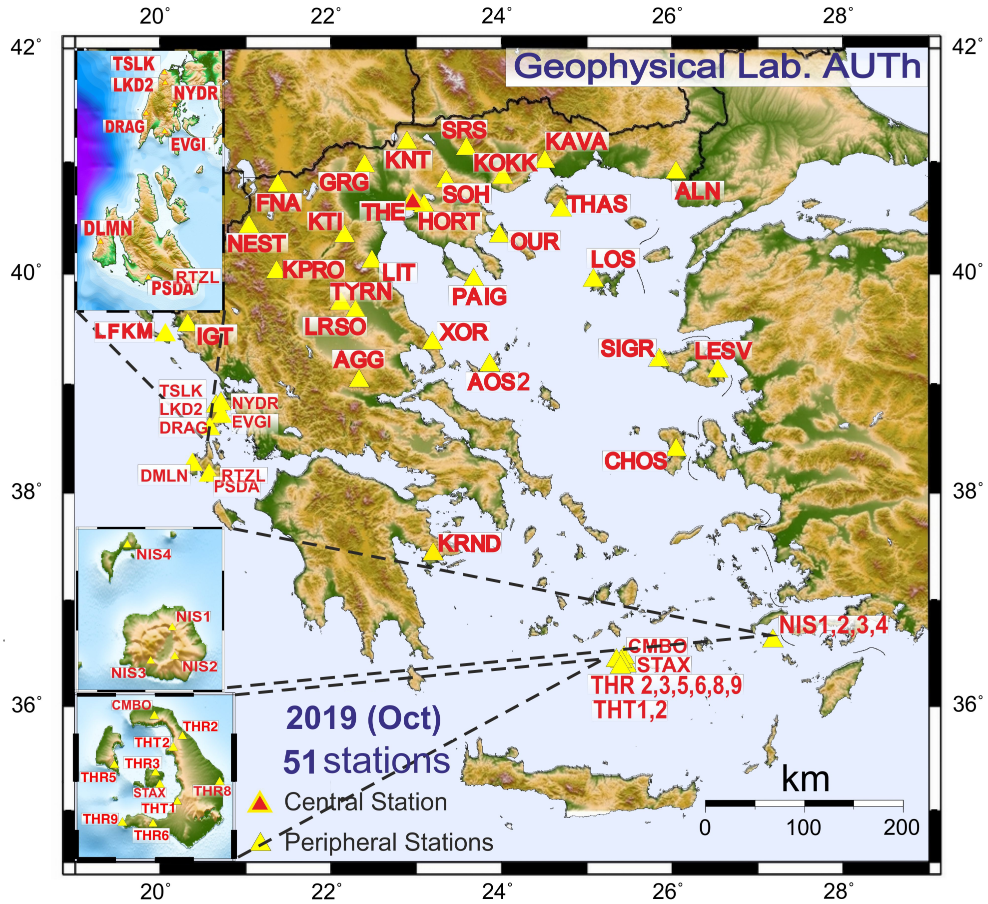

Figure 6.3: *Geographical distribution of the 51 AUTHnet stations in operation at the time of writing (October 2019). In the insets the special local networks of Cephalonia-Lefkada (top), Nisyros (centre) and Santorini (bottom) are also presented. Older, non-operating, stations are also shown (see Table 6.1) (modified from Vamvakaris, 2018).*

months later in 2015 (*Papadimitriou et al.*, 2017).

In **2015 (11th phase)**, two more stations were added in E. Macedonia, in Kokkinohori-Kavala (KOKK) improving the detectability in the area of the Strymon gulf (N. Aegean Sea) and in Tyrnavos (TYRN) in Thessaly.

In 2017 **(12th phase)**, a station was installed on Lesvos Island (LESV) just two weeks after the strong earthquake of $M_w = 6.3$ that hit the island. A couple of months later in **2018** two more stations on Cephalonia island in Ratzakli (RTZL) and on Corfu island in Lefkimi (LFKM) improved the local network on the Ionian Islands. Thus, AUTHnet counts (October 2019) 51 stations in total today.

Figure 6.2 represents the expansion of the network since its establishment in 1981, through a series of maps describing the geographical distribution of AUTHnet stations until 2010 during 4 significant periods (1981, 1996, 2005 and 2010). Its present form is outlined in Figure 6.3.

The change in the number of AUTHnet stations over time is presented in Figure 6.4, where the three basic phases of the network upgrade, in 1989, 1996 and 2003, can be clearly seen.

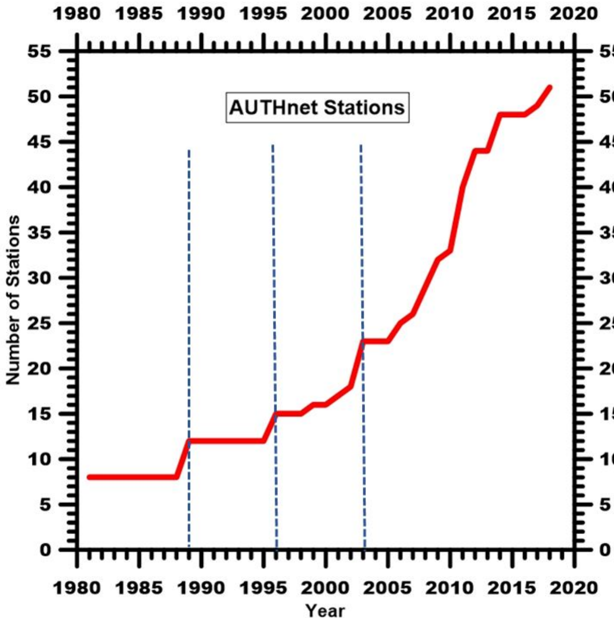

Figure 6.4: *Time evolution of the number of operating stations of AUTHnet, until Oct. 2019 (modified from Vamvakaris, 2018).*

Network Equipment

The initial network (1981) was equipped with 3-component short-period (1 s) analogue S-13 Teledyne-Geotech seismometers (set of 2 horizontals and 1 vertical), while in some cases only vertical S-13 seismometers were used. Additionally, three long-period (20 s) analogue SL-220 Teledyne-Geotech seismometers (one vertical, two horizontals) were installed at the Seismological Station of Thessaloniki (THE). Analogue signals were transmitted through telephone lines from the peripheral stations to the THE-SS. The analogue signal was recorded on a set of Teledyne-Geotech helicorder drums and on 16mm photographic films using a “Develocorder” (Teledyne-Geotech) but, at the same time, it was digitized using a 12-bit, 32-channel, AD converter and recorded to magnetic tapes. That process was managed by a 16-bit PDP11/34 mainframe computer (of Digital Equipment Corporation, DEC), making AUTHnet the first telemetric seismological network in the Balkan region, to be supported by a computer. This system was updated in 1989 with a DEC MicroVAX II 32-bit computer, running a VAX/VMS operating system, which was replaced about 10 years later by a DEC ALPHA 3100 running OpenVMS.

After 2003, modern broadband seismometers were installed in several stations of the network replacing the older short-period S-13. Most of them were CMG-3ESP (100 s – 50 Hz) by Guralp Systems and this is still the most common type of seismometers in AUTHnet stations. Alternatively, CMG-6T (30 s – 50 Hz) sensors were installed in the Nisyros network, CMG-40T (1 s – 100 Hz) and CMG-40T (30 s – 50 Hz) in the Cephalonia-Lefkada network (all by Guralp Systems). Recently, Trillium 120P, 3-component, broadband low-noise seismometers by Nanometrics Inc. were used in new installations. Due to its more suitable characteristics, this seismometer was also selected to replace the CMG-3ESP sensor of the THE-SS in 2014, which, in turn, had replaced the old analogue S-13 in 2005. Last year, a new-type Trillium 120C seismometer was installed at the KOKK and LESV stations.

During the first years of its operation, the network was pseudo-digital, as the transmitted signal was analogue and then digitized at the receiving end (THE-SS). This situation was changed when the first 24-bit HRD-24 digitizers by Nanometrics were used in some stations, digitizing in-situ the signal and transmitting it to THE-SS. Later, Trident 24-bit digitizers with a typical dynamic range of 142 dB, working with a Janus-IP communication controller by Nanometrics, replaced some old HRD-24 digitizers. Since 2006, Taurus digitizers by Nanometrics were deployed as a portable 24-bit digital seismograph, working on 3 channels in a dynamic range of more than 141 dB. In some other cases, REFTEK RT130 by Trimble, wave24 by MicroStep-MIS, CMG-DM24 by Guralp Systems, Smart-24 by Geotech Instruments LLC, were used. Lately, 24-bit Centaur digital recorders by Nanometrics were obtained. Table 6.1 lists in detail the current instrumentation of all 51 operating stations of AUTHnet.

***Table 6.1:** Current (October 2019) station list and instrumentation of the stations of AUTHnet*

#	Station	Lat deg	Long deg	Elevation m	Seismometer	Controler	Digitizer	Initial Installation
1	AGG	39.0211	22.3360	625	TRILLIUM 120P	JANUS	TRIDENT	1989
2	ALN	40.8957	26.0497	110	CMG-3ESP/100	JANUS	TRIDENT	1989
3	AOS	39.1654	23.8639	230	CMG-3ESP/100	-	TAURUS	1996
4	CHOS	38.3869	26.0506	854	CMG-3ESP/100	-	CENTAUR	2006
5	FNA	40.7817	21.3836	806	CMG-40T/30	-	HRD-24	1989
6	GRG	40.9558	22.4029	600	CMG-3ESP/100	-	TAURUS	1981
7	HORT	40.5978	23.0995	925	CMG-3ESP/100	JANUS	TRIDENT	2006
8	IGT	39.5315	20.3299	262	CMG-3ESP/100	-	HRD-24	1989
9	KAVA	40.9941	24.5119	95	TRILLIUM 120P	-	CENTAUR	2008
10	KNT	41.1620	22.8980	380	CMG-3ESP/100	-	HRD-24	1981
11	KOKK	40.8178	23.9992	261	TRILLIUM 120C	-	TAURUS	2015
12	KPRO	39.9549	21.3632	837	CMG-3ESP/100	-	TAURUS	2011
13	KRND	37.3830	23.1502	140	CMG-3ESP/100	-	TAURUS	2010
14	KTI	40.3929	22.1165	1329	S-13	JANUS	TRIDENT	2001
15	LESV	39.1074	26.5613	20	TRILLIUM 120C	-	TAURUS	2017
16	LIT	40.1033	22.4892	568	CMG-3ESP/100	JANUS	TRIDENT	1981
17	LOS	39.9330	25.0810	460	S-13	JANUS	TRIDENT	1996
18	LRSO	39.6713	22.3917	78	CMG-40T/1	-	REFTEK-130	2011
19	NEST	40.4147	21.0489	1056	TRILLIUM 120P	JANUS	TRIDENT	2008
20	OUR	40.3325	23.9791	117	CMG-3ESP/100	-	CENTAUR	1981
21	PAIG	39.9363	23.6768	217	CMG-3ESP/100	-	TAURUS	1981
22	SIGR	39.2114	25.8553	92	CMG-3ESP/100	JANUS	TRIDENT	2007
23	SOH	40.8206	23.3556	731	TRILLIUM 120P	-	TAURUS	1981
24	SRS	41.1087	23.5950	314	CMG-3ESP/100	JANUS	TRIDENT	1981
25	THAS	40.6064	24.7194	67	CMG-3ESP/100	-	TRIDENT	2012
26	THE	40.6319	22.9628	132	CMG-6T/30	JANUS	TRIDENT	1981
27	TYRN	39.7110	22.2325	151	TRILLIUM 120P	-	CENTAUR	2015
28	XOR	39.3660	23.1918	541	CMG-3ESP/100	-	TAURUS	1996
SANTORINI LOCAL NETWORK								
29	CMBO	36.4709	25.4056	108	TRILLIUM 120P	-	TAURUS	2011
30	STAX	36.3993	25.4045	20	CMG-40T/30	-	DM-24	2012
31	THR2	36.4469	25.4354	220	S-13	JANUS	TRIDENT	2008
32	THR3	36.4091	25.4008	71	S-13	JANUS	TRIDENT	2003
33	THR5	36.4172	25.3479	180	S-13	JANUS	TRIDENT	2003

Continued on next page

#	Station	Lat deg	Long deg	Elevation m	Seismometer	Controler	Digitizer	Initial Installation
34	THR6	36.3562	25.3975	119	S-13	JANUS	TRIDENT	2003
35	THR8	36.4070	25.4788	30	S-13	JANUS	TRIDENT	2001
36	THR9	36.3577	25.3569	54	S-13	JANUS	TRIDENT	2011
37	THT1	36.3858	25.4296	0	S-13	-	SMART-24	2011
38	THT2	36.4351	25.4218	338	CMG-3ESP/120	-	REFTEK-130	2011
NISYROS LOCAL NETWORK								
39	NIS1	36.6023	27.1782	378	CMG-3ESP/100	-	TAURUS	2008
40	NIS2	36.5780	27.1808	400	CMG-6T/30	-	WAVE-24	2009
41	NIS3	36.5742	27.1557	271	CMG-6T/30	-	WAVE-24	2009
42	NIS4	36.6717	27.1314	-	CMG-6T/30	-	WAVE-24	2009
CEPHALONIA-LEFKADA LOCAL NETWORK								
43	DLMN	38.2385	20.3734	370	CMG-40T/1	-	REFTEK-130	2014
44	DRAG	38.6839	20.5746	348	CMG-40T/1	-	REFTEK-130	2014
45	EVGI	38.6210	20.6560	249	CMG-40T/30	-	REFTEK-130	2012
46	LKD2	38.7889	20.6578	485	CMG-3ESP/100	JANUS	TRIDENT	2008
47	NYDR	38.7135	20.6983	212	CMG-40T/1	-	REFTEK-130	2014
48	PSDA	38.1140	20.5841	48	CMG-40T/30	-	REFTEK-130	2014
49	TSLK	38.8249	20.6554	212	CMG-40T/1	-	REFTEK-130	2014
50	RTZL	38.0760	20.7715	103	TRILLIUM 120C	-	REFTEK-130	2018
51	LFKM	39.4465	20.0608	1	LE-3D/1sec	-	REFTEK-130	2018
OLDER STATIONS (NOT OPERATING)								
	LKD	38.7074	20.6505	1171				
	MEV	39.785	21.2290	1500				
	THR1	36.3712	25.4597	522				
	THR4	36.46	25.3974	220				
	THR7	36.4224	25.4284	315				

Data Transmission

Typical telephone lines (using carriers of 1020 Hz, 1360 Hz and 1700 Hz for the vertical, N-S and E-W components, respectively) and analogue modems (USRobotics and 3Com) were firstly used to transmit the signal from the seven initially installed peripheral stations (SOH, LIT, GRG, PAIG, KNT, OUR and SRS) to the Central Seismological Station in Thessaloniki (THE-SS).

Initially, the data from some stations (such as LOS, AOS and XOR) were delivered using radio modems (MR400 by RACOM), in the UHF band. Later on, as internet connectivity got faster, cheaper and easier to acquire, DSL connections (PSTN or ISDN) became prominent. Where necessary, RM4 multiplexers by Nanometrics were employed for the transmission over IP, while at several stations (e.g. AGG, KNT, SRS, CHOS, etc.) satellite links are used. Recently, communication over GSM/3G protocol was implemented at LIT.

6.1.3 Data Aquisition

Until 2005, there were four operational seismological networks monitoring the seismic activity in Greece: the networks of the Institute of Geodynamics of National Observatory of Athens (NOA), the Geophysical Laboratory of the Aristotle University of Thessaloniki (AUTH), the Seismological Laboratory of University of Athens (NKUA) and the Seismological Laboratory of University of Patras (UPAT). In 2005, a national project was carried out, financially supported by the Ministry of Development of Greece, in order to unify these networks into one dense national network named Hellenic Unified Seismic Network, HUSN. This project was completed in 2007 and the HUSN started its operation in 2008. Thus, data from all participating networks are now shared in real-time to all four participating institutions, giving them direct access to the records of a unified seismic network of more than 150 stations, all over Greece.

Moreover, in an effort to further improve its detectability, AUTHnet interacts with several European institutions such as GEOFON (Germany), MEDNET (Italy), KOERI (Turkey), IGEWE (Albania), NIGGG-BAS (Bulgaria), SOS (N. Macedonia) and SSS (Serbia) who provide their real-time data and receive data from selected AUTHnet stations. This interaction with neighbouring institutions is critical, mostly in cases of strong or damaging earthquakes out of or close to the network boundaries. At the same time, the opportunity for wider international scientific collaboration is offered.

Data Management

In order to manage all the seismological data transmitted to the THE-SS the NaqsServer system by Nanometrics was used for about 15 years until May 2019. It was working simultaneously on four acquisition servers (both physical and virtual), running on GNU/LINUX. The data acquisition system was receiving real-time data from digitizers through UDP/IP, distributing the data through TCP/IP, saving them on ringbuffers, creating and checking all the triggers and detecting the events. Finally, the Nanometrics acquisition system consists of several utilities to monitor the state-of-health for all the stations and to send calibration commands for the managed instruments remotely.

In May 2019, SeisComP3 software by GFZ Potsdam and Gempa GmbH replaced the outdated NaqsServer. SeisComP3 is the most known open seismological software for data acquisition, processing, distribution and interactive analysis. The latest stable SeisComP3 version (Jakarta 2018.327.p17) is currently used in AUTHnet.

Seedlink protocol is used for data exchange in the Standard for the Exchange of Earthquake Data format (SEED) with other servers in real time, through TCP/IP. For data exchange with other acquisition systems (such as Nanometrics or Reftek), other appropriate plugins are used.

All real time data, including waveforms, are stored on two different servers running CentOS Linux 7. SeisComP3 uses a database to save all information related with station metadata and seismological data processing, such as arrival times, epicenter estimations, magnitude calculations etc. The database management used is the latest MariaDB Database Engine, a successor of MySQL.

Depth	Thickness km	Velocity km/s	References
Upper sed. layer	1.5	5.0	*Scordilis*, 1985
Layer 1	18.5	6.0	*Panagiotopoulos*, 1984
Layer 2	12.5	6.6	*Panagiotopoulos*, 1984
Half-space	-	7.9	*Panagiotopoulos*, 1984

Table 6.2: *Details on the two-layer over a half-space velocity model and the upper sediment layer used in the earthquake-location procedure.*

Analysis

For daily earthquake analysis SCOLV is used, which is the main interactive tool of SeisComP3 to revise or review the original information such as picks, locations, depths, time, magnitudes and event association. Earthquake parameters and arrival times are stored in the typical AUTOLOC3 format while preliminary bulletins and seismic catalogues are created. The events are analysed on a 24/7 basis. After review, final monthly bulletins are published.

The earthquake-location algorithm NonLinLoc (*Lomax et al.*, 2000) is used to manually estimate the focal parameters. This is a set of programs for velocity model construction, travel-time calculation and earthquake location in 3D structures. The selected velocity model is the one proposed by *Panagiotopoulos* (1984) and *Panagiotopoulos and Papazachos* (1985), which consists of two-layers over a half-space. Additionally, an upper sediment layer (*Scordilis*, 1985) is also considered (Table 6.2).

Near real-time automatic epicenter estimation is also provided by SeisComp3 using LocSat locator by *Bratt and Nagy* (1991). In this case, the IASP91 predefined travel-time table proposed by *Kennett and Engdahl* (1991) and the responsible IASPEI Sub-Commission is implemented for earthquake location and phase identification.

Storage

Raw data are stored in temporary ring-buffers with capacity of more than 90 days (depending on station), in 100 samples/s. Over 500 channels flow per day in ring-buffers resulting in a daily need of about 5.5 GB storage (about 2 TB per year). All located events are stored in the SeisComP3 database, in the SEED format. Additionally, all continuous data (waveforms) are also stored in the European Integrated Data Archive (EIDA, `http://www.orfeus-eu.org/eida/`) national node.

Magnitude calculation

During the earthquake analysis procedure the local magnitude (M_L) is calculated, adopting the multi-parametric equation initially proposed by *Bakun and Joyner* (1984):

$$M_L = \log(A) + n \cdot \log\left(\frac{R}{100}\right) + K(R - 100) + 3.0, \tag{6.1}$$

where A is the zero-to-peak amplitude (in mm) on a typical W-A seismograph (recorded or synthesized), R is the hypocentral distance (in km), n is the geometrical spreading factor and K is the anelastic attenuation coefficient. For the routine analysis the values n=1.11 and K=0.00189, estimated by *Hutton and Boore* (1987) for earthquakes of California, are adopted. The amplitude used for each station corresponds to the mean value of the maximum zero-to-peak amplitudes measured on the two horizontal components of synthetic Wood-Anderson (SW-A) records. The final local magnitude, M_L, of each earthquake is calculated as the mathematical mean value of the individual magnitudes provided by each station, after applying 90 % confidence limits (± 1.65 SD).

Recently, there was a study using a large number of SW-A records of the HUSN (Hellenic Unified Seismic Network) in an effort to define values of geometrical spreading factor n and of anelastic attenuation coefficient K representative for the area of Greece (*Scordilis et al.*, 2015). The final relation proposed in this work for M_L estimation in Greece is:

$$M_L = 1.319 \cdot \log\left(\frac{R}{100}\right) + 0.00226(R - 100) + 3 + c_i, \tag{6.2}$$

where c_i is the individual correction due to the site conditions of each station. We are currently running tests to evaluate Equation 6.2 in comparison with Equation 6.1.

Quality Analysis of GeoLab Bulletin

As a product of routine analysis, monthly bulletins starting from 1995 are published online on our website. The catalogue that is formed from these bulletins includes about 94,000 earthquakes that occurred within the area 33–43°N, 18–30°E.

The completeness of the catalogue, i.e. the magnitude value M_c above which a bulletin is expected to contain 100 % of seismic events, varies in space as well as with time. This is due to the inhomogeneous coverage of the region by seismological stations as well as to possible expansions of the participating seismological networks and/or development of more sophisticated sensors. Several methods have been proposed for the determination of completeness (e.g. *Wyss et al.*, 1999; *Wiemer and Wyss*, 2000; *Woessner and Wiemer*, 2005), essentially relying on the estimation when the reported seismicity no longer follows the Gutenberg-Richter relationship (*Zuniga and Wyss*, 1995). The catalogue's completeness was analysed by applying a combination of these methods.

Completeness variation with time

To determine the time-dependency of the catalogue's completeness, sample windows of several sizes were considered and repeated estimations after bootstrapping were attempted. Three methods have been applied, namely the maximum curvature method (MAXC), the goodness of fit method (GoF) with confidence limits 90 % and 95 % and the entire magnitude range method (EMR) with the help of the Zmap software package (*Wiemer*, 2001).

Figure 6.5 presents the time variation of the completeness magnitude, M_c, as obtained with the combination of the three methods, mentioned above. The examination of the corresponding plot suggests the presence of rather stable M_c values, for certain time intervals. On the basis of this temporal stability, the following general completeness time periods are proposed:

- 1995 – 2003, $M \geq 3.3$,

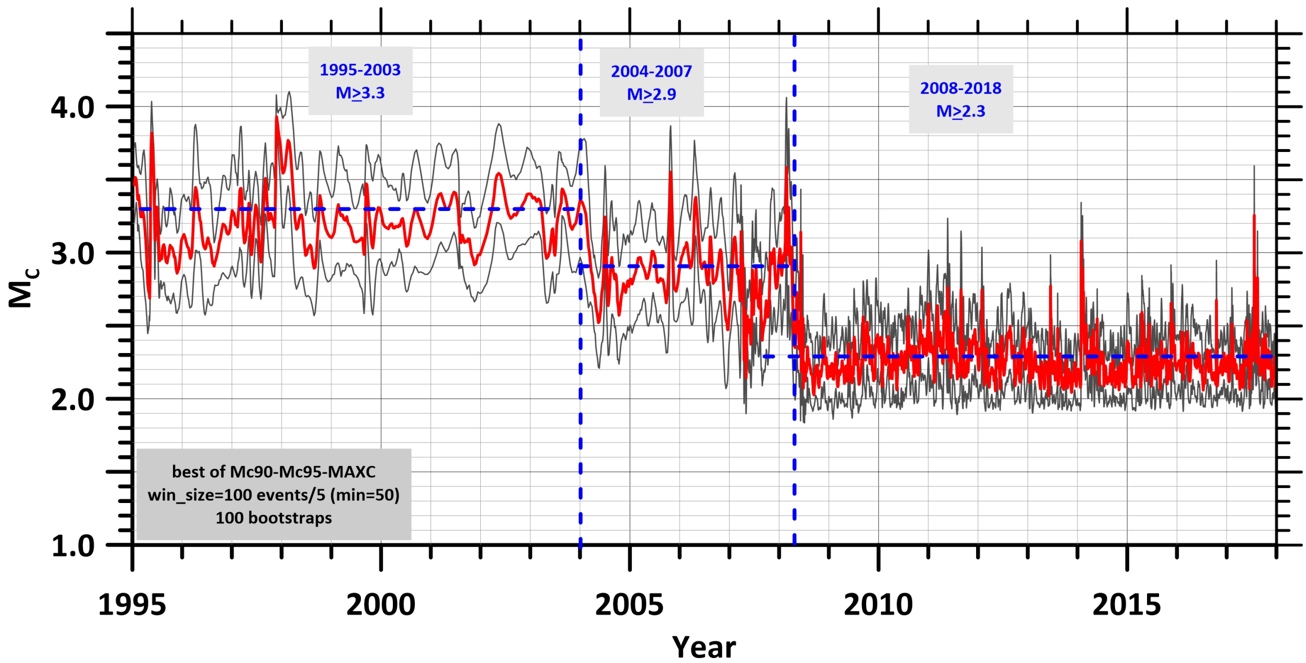

Figure 6.5: *Time variation of the completeness magnitude, Mc, for the AUTHnet catalogue after the combined application of the maximum curvature (MAXC), the goodness of fit (GoF) with confidence limits 90 % and 95 % and the entire magnitude range (EMR) methods (Zmap software, Wiemer, 2001). Gray lines represent the uncertainties revealed after resampling (sample size 100 with 100 bootstraps).*

- 2004 – 2007, $M \geq 2.9$,
- 2008 – 2018, $M \geq 2.3$.

The defined completeness periods are affected by the main expansion phases of AUTHnet. More specifically:

(a) The period (2004-2007) is affected by the 5th phase of the network's expansion that improved its detectability (see Chapter 6.1.2) reducing the completeness magnitude from M_c=3.3 to M_c=2.9.

(b) A further reduction of the completeness level to M_c=2.3 is observed after 2007 due to the 6th and 7th phases of the network's expansion.

Completeness Variation in Space

The spatial variation of the M_c values for each of the previously defined completeness periods has also been analysed, in order to further exhibit the temporal variations throughout the broader area of Greece (Figure 6.6).

A grid of 0.10°×0.10° covered the whole study region. For each complete time-period, circular areas of 100 km radius, centred at each node of the grid were considered. The M_c value corresponding to the earthquakes of each circular area was estimated again by the combination of MAXC, GoF 90 %, GoF 95 % and the EMR method (Zmap software package, *Wiemer*, 2001). The derived M_c values were used to produce contour maps showing its spatial distribution for each complete period (Figure 6.6).

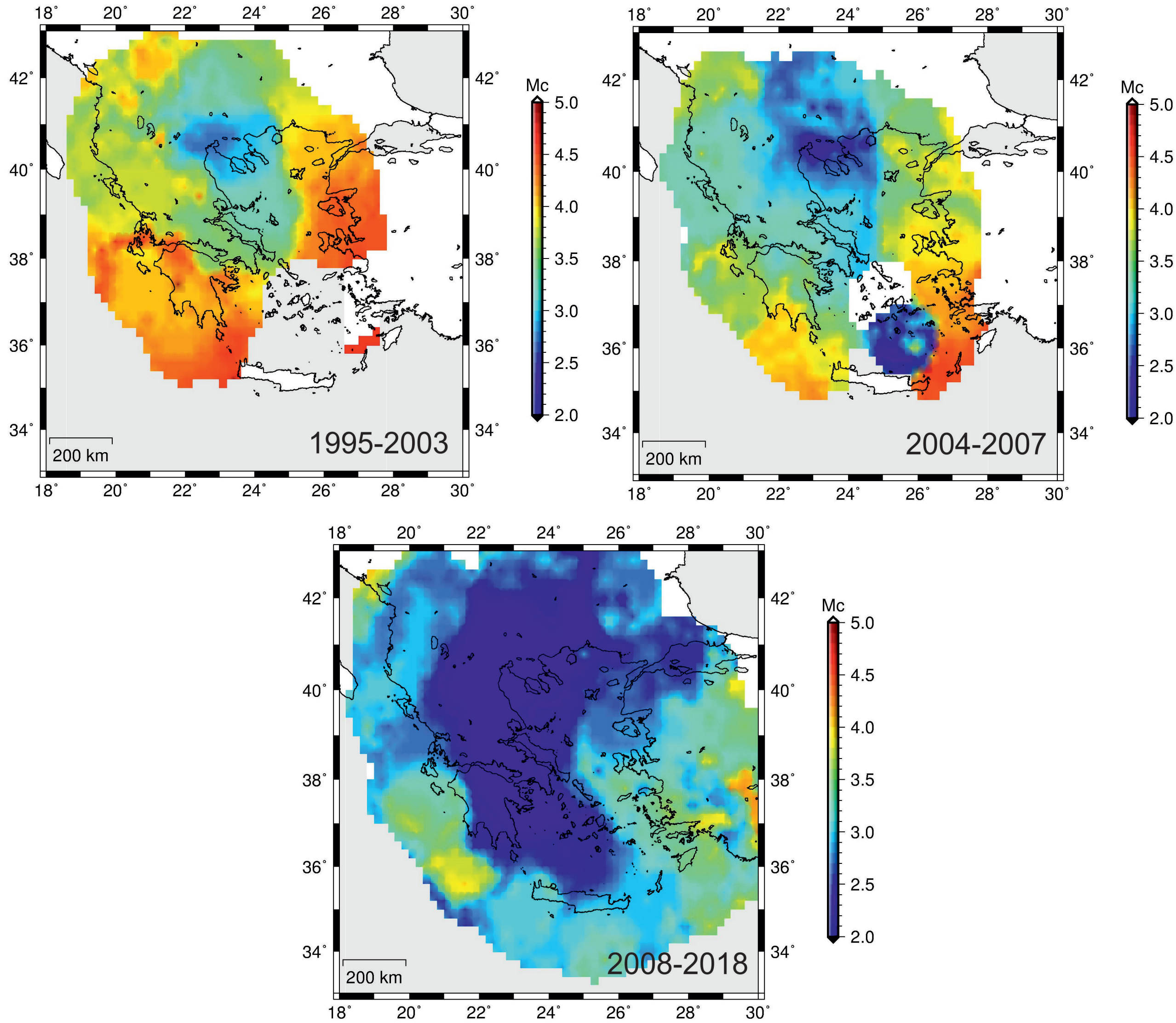

Figure 6.6: *Spatial variation of the completeness magnitude, Mc, of the catalogue produced by AUTHnet.*

6.1.4 Aims and Social Contribution

Aims and Services Provided

AUTHnet operates 24 hours per day, 365 days per year and its main purpose is the continuous near real-time monitoring and processing of seismic data. The dense network provides the opportunity for a rapid manual determination (in about 15–20 minutes) of the location and magnitude of all earthquakes (M>2.5) that occur in the broader area of Greece. Automatically produced preliminary determinations of the focal parameters (based on SeisComP software) for every event are also performed within one minute of the event's occurrence. In case of a destructive event, all available information is disseminated to national and local authorities, such as the Earthquake Planning and Protection Organization (E.P.P.O) and the General Secretariat of Civil Protection. It is also a priority for the staff of THE-SS to provide rapid and valid information to the media and to the public, preparing also announcements, whenever necessary, about the evaluation of on-going seismic activity.

Several types of information are presented on the THE-SS website (`http://seismology.geo.auth.gr/ss`), where both automatic (real-time) and revised (manual, near real-time) locations for the current seismic activity are presented on a map. In case of a disruptive earthquake (e.g. of $M > 4.0$) additional details are provided. As the network is now equipped with broadband sensors, near-real time moment tensor computations are performed and published online. Since 2013, a semi-automatic process for a near-real-time evaluation of the evolution of seismic excitations (*Teza*, 2011) is also applied. The respective results are published on-line and are updated daily until the end of the excitation under surveillance. Finally, seismicity maps, preliminary and revised earthquake catalogues as well as monthly earthquake bulletins are also available in the THE-SS website.

The international scientific community receives detailed information about the seismic activity in Greece as THE-SS shares this information with international seismological agencies dealing with the collection of such data (e.g. EMSC, ISC, NEIC). THE-SS also contributes phase readings of long-distance moderate to large earthquakes that occur globally.

The continuous technical and spatial upgrade of the network assures the high quality of the data collected. The number of recorded earthquakes is increasing, data of higher accuracy are produced, while the uncertainties on epicenter and depth determination are less than 5 km. At the same time, the network's detectability keeps improving due to the installation of new stations. Thus, in areas with azimuthal gaps of less than 180° the network's detectability is higher with the minimum recorded (detected) magnitude dropping below 2.0.

Thus, the completeness magnitude for the broader Thessaloniki area is M_c=2.9 since 1981 and M_c=2.4 since 1990 (*Vamvakaris et al.*, 2016). Recently, the completeness in this area is further improved with M_c=2.0, while for the rest of the network area the completeness magnitude increases to 2.5 or more, especially close to the network boundaries (Figure 6.6). In many cases, local networks (e.g. Santorini and Cephalonia-Lefkada networks) are able to provide reliable focal parameters for earthquakes with magnitudes even smaller than M=1.0.

Between 1995 and 2006, 1,000 to 1,500 regional events were recorded per year and analysed by AUTHnet. Some 4,200 earthquakes were recorded in 2007 (the annual number nearly quadrupled), while this number increased to 6,600 in the following year (2008). In 2013 the recorded earthquakes reached 7,200. During the last four years, the network detected more than 8,000 events/year, while in 2015 this number exceeded 9,000. This means that around 25 regional earthquakes were recorded daily, the focal parameters of which were manually calculated by GeoLab scientific staff. This large number of earthquakes is directly connected with the continuous qualitative and quantitative improvement of AUTHnet. Thus, from 2004 onward, it became feasible to conduct detailed studies on disturbing regional seismic excitations (e.g. in Andravida with M=6.5 in 2008; Lemnos with M=5.9 and Amfiklia with M=4.9 in 2013; Zakynthos with M=4.7, Cephalonia with M=6.1, Samothraki with M=6.3 and Evoikos gulf with M=5.3 in 2014; Lefkada with M=6.4 in 2015; Ioannina with M=5.3 in 2016; Lesvos with M=6.3 and Kos with M=6.6 in 2017; Zakynthos with M=6.8 in 2017).

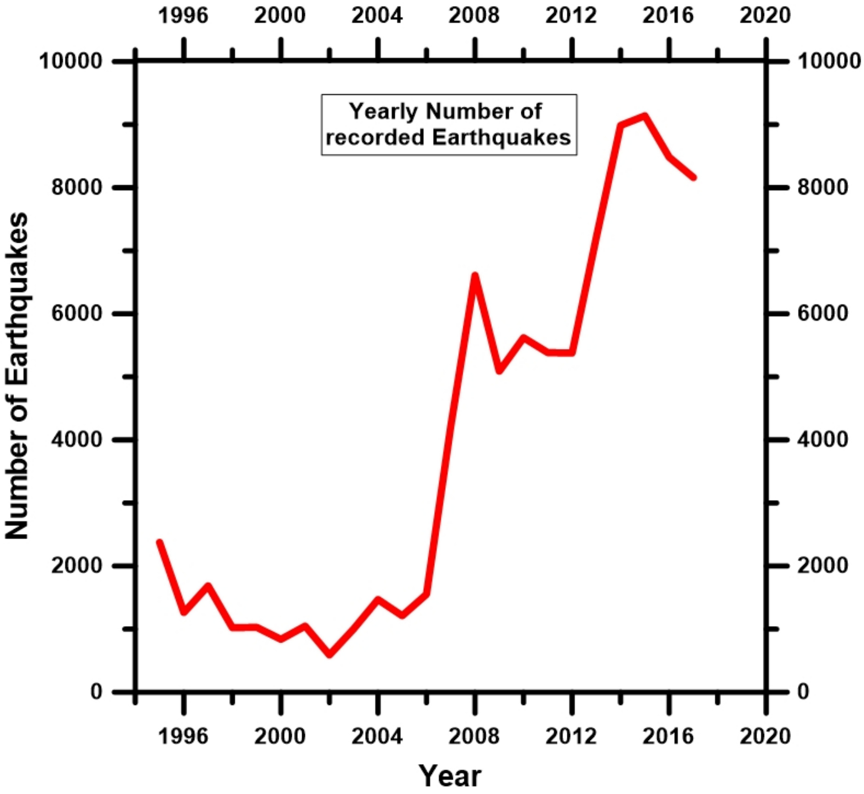

Figure 6.7: *Number of regional earthquakes recorded by AUTHnet, during the period 1995-2017 (Vamvakaris, 2018).*

AUTHnet Contribution to Society

Besides their research profile, GeoLab and THE-SS also have an educative mission. Thanks to the seismological network and its data collection, undergraduate students are involved with applied seismology and many postgraduate students and PhD candidates elaborate their theses and work on several seismological and geophysical projects. It is also important to note that in the framework of the continuous flow of information to the public, the scientists of THE-SS give several lectures to elementary and high school students, transferring knowledge about earthquakes and protection measures. Highschool students have the opportunity to visit the Central Seismological Station, see the instruments and experience the routine of a seismologist on duty. Lectures focused on specific topics are also given to rescue teams and members of the Civil Protection Organization of Greece.

In the last 5 years, taking advantage of the project “AUTH Sundays”, organized by the Aristotle University, citizens have the opportunity to visit the Central Seismological Station and get more familiar with earthquakes, by watching relevant presentations and speaking with seismologists. The main target, through this permanent interaction with society, is to get people (and especially the young kids) more familiar with earthquakes by teaching them how to act and how to protect themselves when a strong earthquake occurs.

The Geophysical Laboratory is always open to invitations to participate in activities, exhibitions and festivals, aiming to better inform the public on seismic building codes and protection issues.

6.1.5 Future Plans

A continuous improvement of the geographical density of AUTHnet by installing more stations is always in the plans. An instrumental upgrade is coming soon, as new compact 3-component Trillium seismometers (120 s - 100 Hz) are already available to replace the older ones. The time of correspondence and reaction in case of felt earthquakes is very important, thus it is necessary to further reduce the time needed for accurate estimation of the focal parameters of disturbing earthquakes. In this sense, more reliable automatic alerts could be very helpful, mostly in cases of aftershock sequences. Another realistic target for the next period is to offer automatically produced near real-time shake maps, when a strong earthquake occurs. These maps could be very useful to the authorities, in order to have a more detailed instant view of possibly damaged sites and, therefore, to better prepare their actions.

AUTHnet plans to start permanent communication with selected persons of authorities by sending direct notice through e-mail or SMS, when an earthquake occurs. That service could be extended to the public, so everybody could receive an automatic e-mail informing them about the evolution of an ongoing seismic excitation.

Apart from the obvious contribution to earthquake monitoring, a result of the ongoing qualitative and quantitative improvement of the produced seismological data is the better understanding and interpreting of the geodynamic phenomena that take place in Greece. Such data are powerful tools for scientists who are involved with geodynamics to study the crustal structure, the complexity of lithosphere and the upper and deeper mantle, as well. These are significant research areas that can lead to important breakthroughs in better understanding the continental dynamics and earthquake mechanics.

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