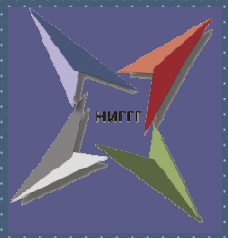
International School and Workshop
NONLINEAR MATHEMATICAL PHYSICS AND NATURAL HAZARDS
November 28 – December 2, 2013, Sofia

Seismic Monitoring and Instrumentation for Earthquake Engineering Application in Bulgaria

Kiril Hadjiyski, Svetoslav Simeonov



National Institute of Geophysics, Geodesy and Geography,
Bulgarian Academy of Sciences

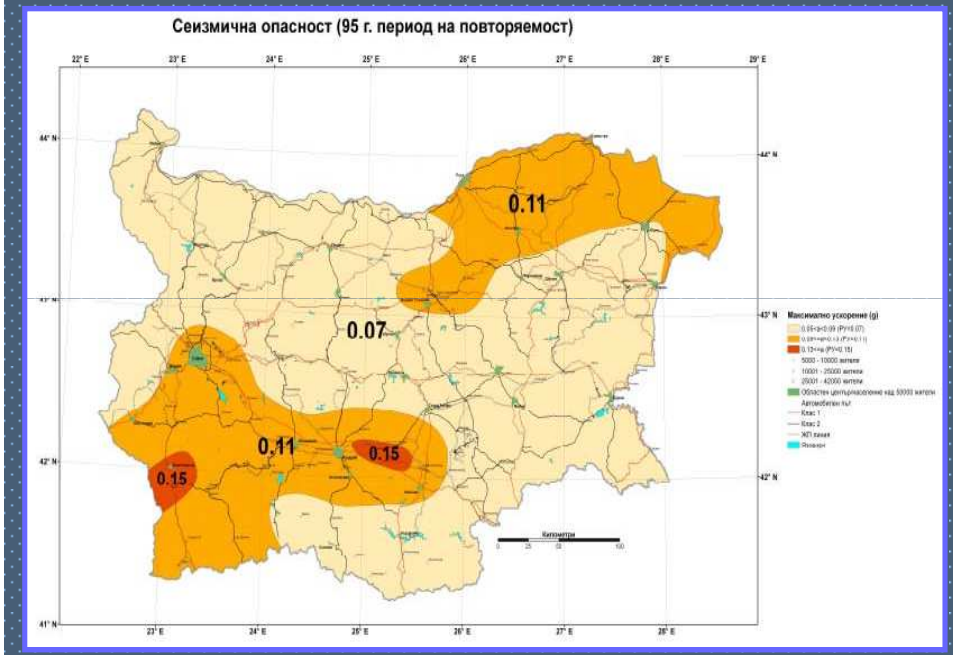
MAJOR DAMAGING HISTORICAL EARTHQUAKES

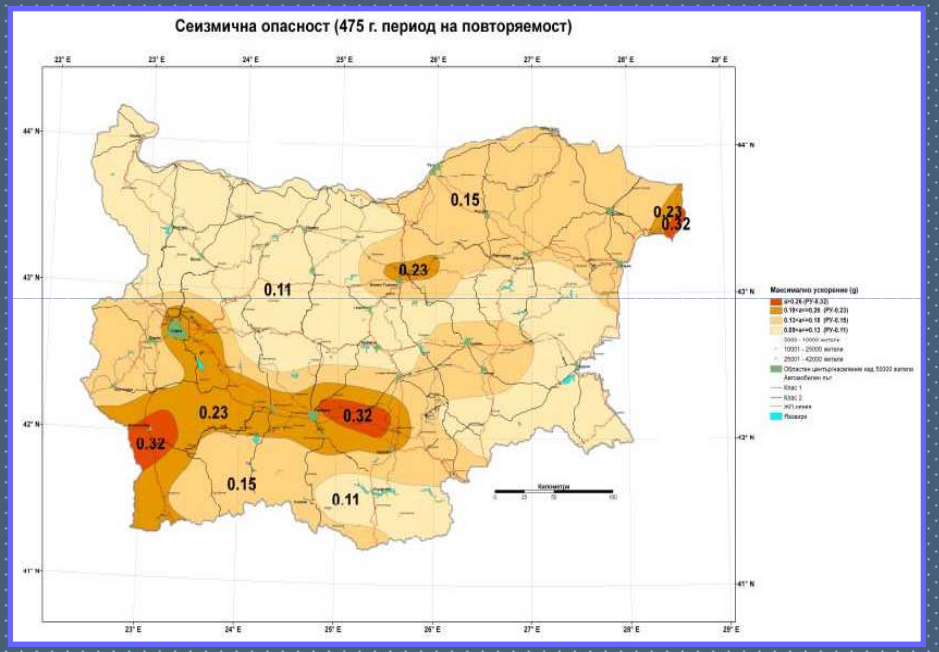
Date	Location	M	H, km	Io
1818	Sofia	-	-	VIII-IX
1858	Sofia	6.3	-	IX
31.03.1901	Shabla	7.2	14	X
04.04.1904	Simitli	7.3	15	IX-X
04.04.1904	Krupnik, Kresna	7.8	18	X
08.10.1905	Krupnik, Kresna	6.4	19	VIII
15.021909	Yambol	6.0	4-8	VIII
14.06.1913	G. Orya-hovitza	7.0	15	IX-X

Date	Location	M	H, km	Io
18.10.1917	Sofia	5.2	6	VII-VIII
14.04.1928	Chirpan	6.8	10	IX
18.04.1928	Popovitza, Plovdiv	7.1	16	IX-X
25.04.1928	Galabovo	5.7	13	VIII
23.08.1942	Razgrad	5.1	10	VII
30.06.1956	Shabla	5.5	20	VII
03.11.1977	Velingrad	5.3	8	VII
07.08.1986	Stragitza	5.7		VII-VIII
22.05.2012	Pernik	5.8	10	VII-VIII

NIGGG (Hristoskov & Solakov, 2009)

SEISMIC ZONATION
BDS-EN-1998-1 (2010) NA of EUROCODE-8





T_R = 90 years

T_R = 475 years

NIGGG

Contents

- EE department of NIGGG – activities.
- Seismic equipment and experience.
- The National Strong Ground Motion System (SMS).
- In-situ dynamic testing and seismic instrumentation of structures.
- Case study of a RC residential building.
- Results of ambient and earthquake response studies of structures.
- Final Remarks.

Two main streams of activities:

- Strong Ground Motion Monitoring on the territory of Bulgaria – management, maintenance and exploitation of the National SGM System;
- Experimental investigation of the dynamics of buildings, engineering structures and soil/foundation strata – identification of dynamic characteristics.

Geophysical investigations on construction sites.

The experimental complex of the CLSMEE encompasses the following major groups of specialized equipment:

- Multichannel systems for measurement, recording, processing and analysis of seismic tremors and mechanical vibrations of soil/foundation, buildings and structures – K-2 (Kinemetrics), GSR-16PC (GeoSig), SM – 6 (IRIS Instruments), OYO McSeis 170f, OYO McSeis 1500, OYO McSeis 150, VSS (Kinemetrics);
- Excitation set-ups - MTS electronic-hydraulic system for excitation of vibrations in soils and structures; OWS borehole system for vibration excitation in soil media;
- Accelerograph units – analogue: SMA-1 and SMA-2; digital: ETNA, GSR-12, GSR-18 and RefTek (131A).

E x p e r i e n c e:

Professionals from the DEE/CLSMEE have carried out more than 70 large scale field experiments for Earthquake Risk Reduction purposes, solving many pending research and industrial problems. Some of the most significant projects/case studies realized are: NPP Kozloduy and the site of the Belene NPP; Sofia Underground Rail; Sofia Airport; the large dams of Chaira, Belmeken, Kardjali, Draginovo, Tzankov Kamak etc; monuments of national and world cultural heritage (the Rila Monastery, the church St. Sophia, the Antique Theatre in Plovdiv, the Tombul Mosque, renaissance houses, etc.).

Teams of experts from the CLSMEE had performed analysis and evaluation of the damages from strong earthquakes in our country and abroad (Velingrad, Strazhitza, El Asnam, Kobe, Krumovo, Provadiya, Kardjali, Pernik etc.).

P u r p o s e of the SGM System

Provides information about, and related to:

- ✓ the SGM seismicity of Bulgaria;
- ✓ the safety and hazardless operation of important facilities;
- ✓ the needs of governmental institutions, branches and departments of the Civil Protection Directorate and local governments;
- ✓ estimation of probable losses;
- ✓ anti-seismic provisions for new buildings and facilities;
- ✓ seismic vulnerability of the existing building stock;
- ✓ improvement of design codes, targeting reduction of the seismic risk.

History

In the early 80-ties of the XX c. – the beginning.

DEE/CLSMEE – development, management and maintenance.

The analogue network of the SMS comprises

54 accelerographs SMA-1 in 43 locations –

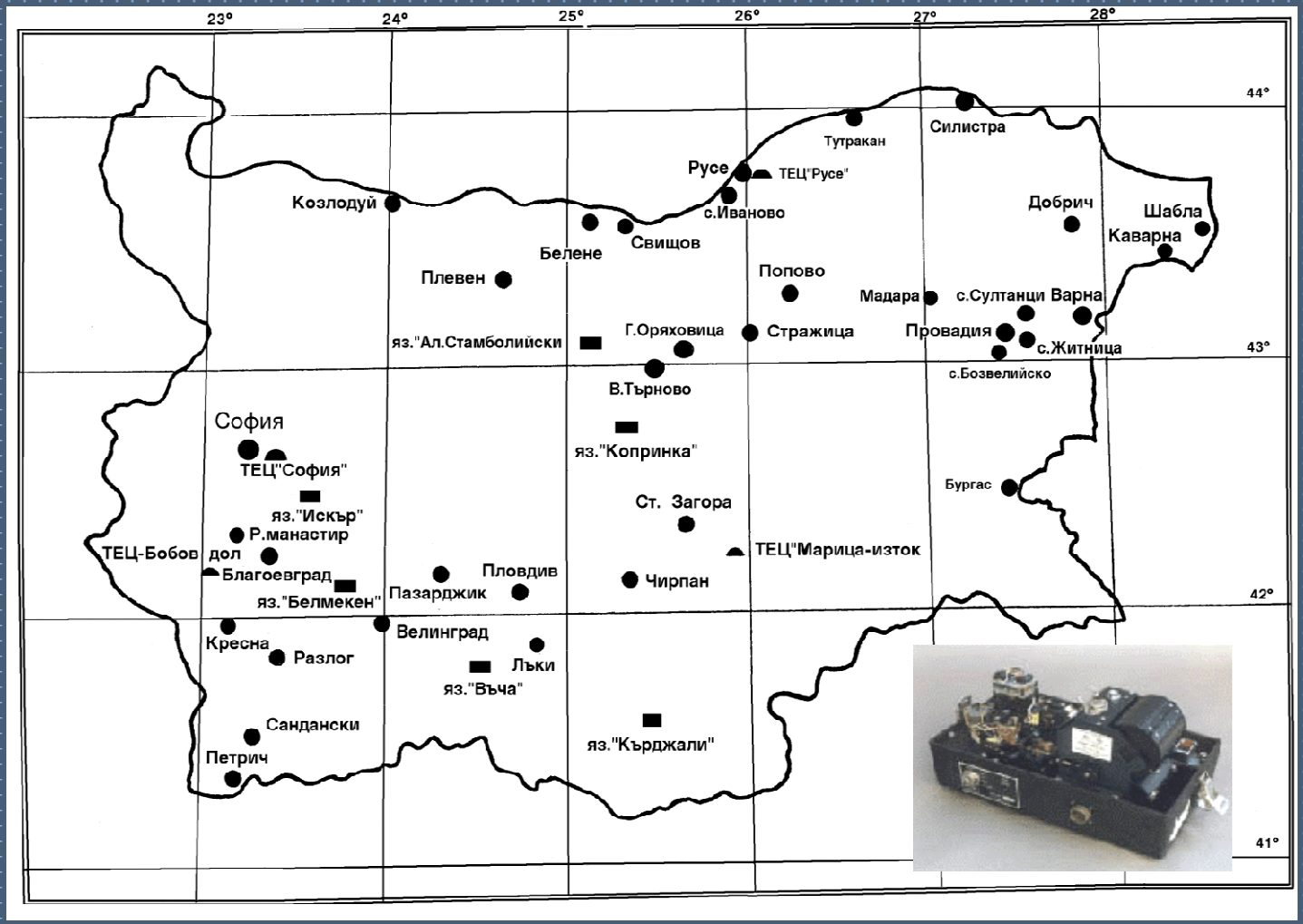
in free field, in buildings and engineering structures.

In 1997 - 5 GSR-12 with 3-D SSA accelerometers for seismic monitoring of monuments of world historic heritage.

Principles:

- ✓ maximum coverage of the most active seismic regions;
- ✓ covering the variety of the structural systems;
- ✓ special emphasis on NPP, TPP, big dams etc.

The analogue network of the SMS



Project for the reconstruction and modernization of the SMS (2004)

- ✓ In 2003 – unsatisfactory condition;
- ✓ Functioning normally – small part;
- ✓ New Digital Nets in the neighbouring Balkan states (>100)

Objective: to reconsider the SMS, reflecting the current trends in the development of similar networks worldwide and to supply it with new digital equipment.

Concept /in observatories of BASc (GPhI, CL of Geodesy)/:

- ➢ minimal new investment;
- ➢ reliable safekeeping and functioning;
- ➢ convenience of exploitation.

In 2004-05 the SMS is reconsidered reflecting current trends - project for upgrading is implemented (20 new digital stations). In 2008-09 a new project for expansion executed (the digital stations became 40). Network coverage – with modern equipment under minimal density.

The ETNA accelerograph /Kinemetrics/

ETNA - *High Dynamic Range Strong Motion Accelerograph*

Data Acquisition

Type: 24 bit Digital Signal Processor

No ch.: 3 Channels

Dyn. range : 108 dB @ 200 sps

Freq. resp.: DC to 80 Hz @ 200 sps

Resolution : 18-bit res. @ 200 sps

Sampl. rate: 100, 200, 250 sps

Input range: ± 2.5V

Sensor

Type: Triaxal EpiSensor FB Accelerometer

Full scale range: ±2g (user selectable)

Bandwidth: DC to 200 Hz

Dynamic range: 155 dB+

Storage

Type: 2 Fully compliant PCMCIA storage slots

32/64 MB Memory Card

The 12-channelled K2 /Kinemetrics/

K2 - *High Dynamic Range Strong Motion Accelerograph*

Data Acquisition

Type: 24 bit Digital Signal Processor

No ch.: 12 Channels

Dyn. range : 114 dB @ 200 sps

Freq. resp.: DC to 80 Hz @ 200 sps

Resolution : 24-bit res. @ 200 sps

Sampl. rate: 20, 40, 50, 100, 200, 250 sps

Input range: ± 2.5V

Sensor

Type: Triaxial/Uniaxial EpiSensor FB Accelerometer

Full scale range: ±0.25g

Bandwidth: DC to 200 Hz

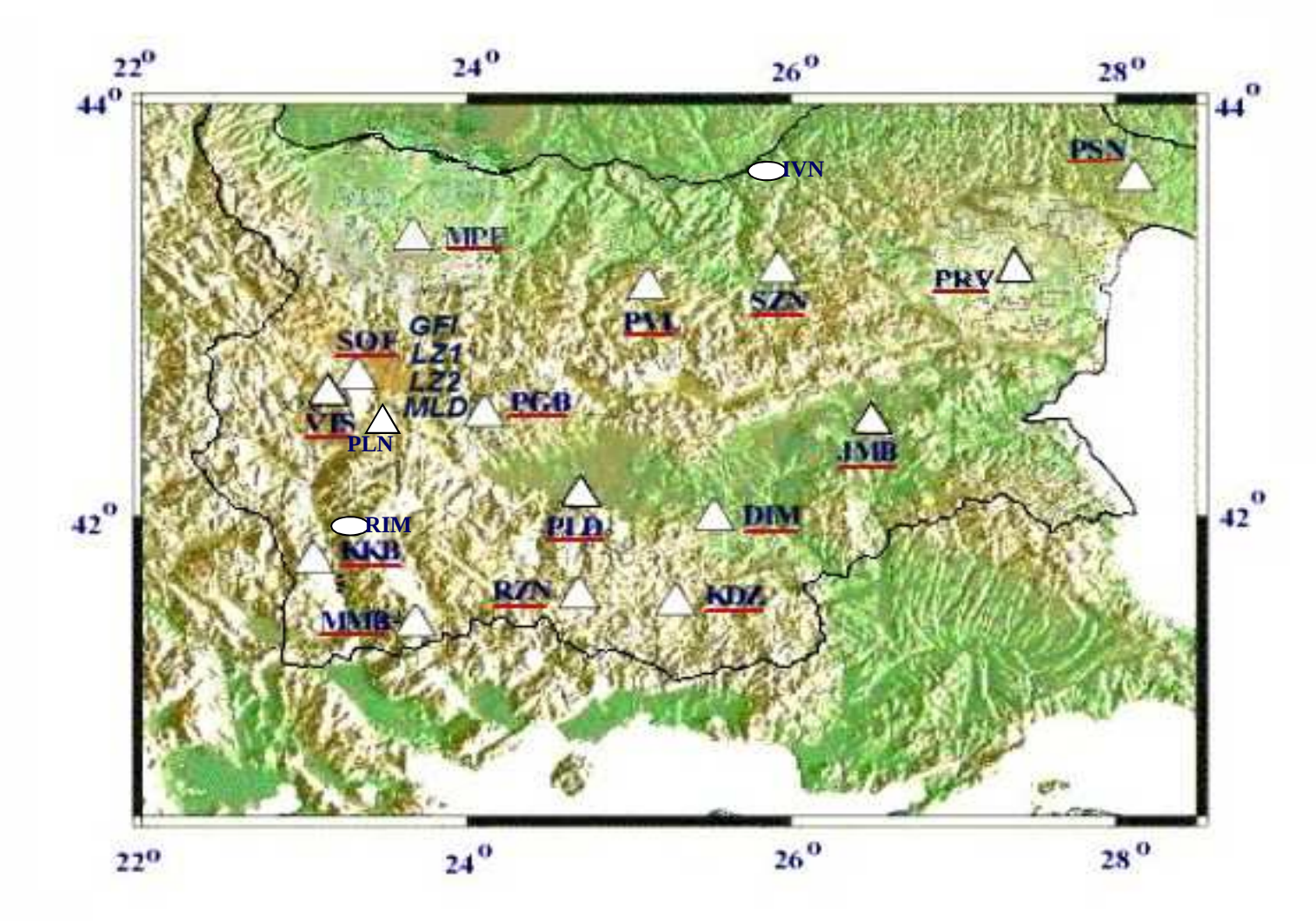
Dynamic range: 155 dB+

Storage

Type: 2 Fully compliant PCMCIA storage slots

32/64 MB Memory Card

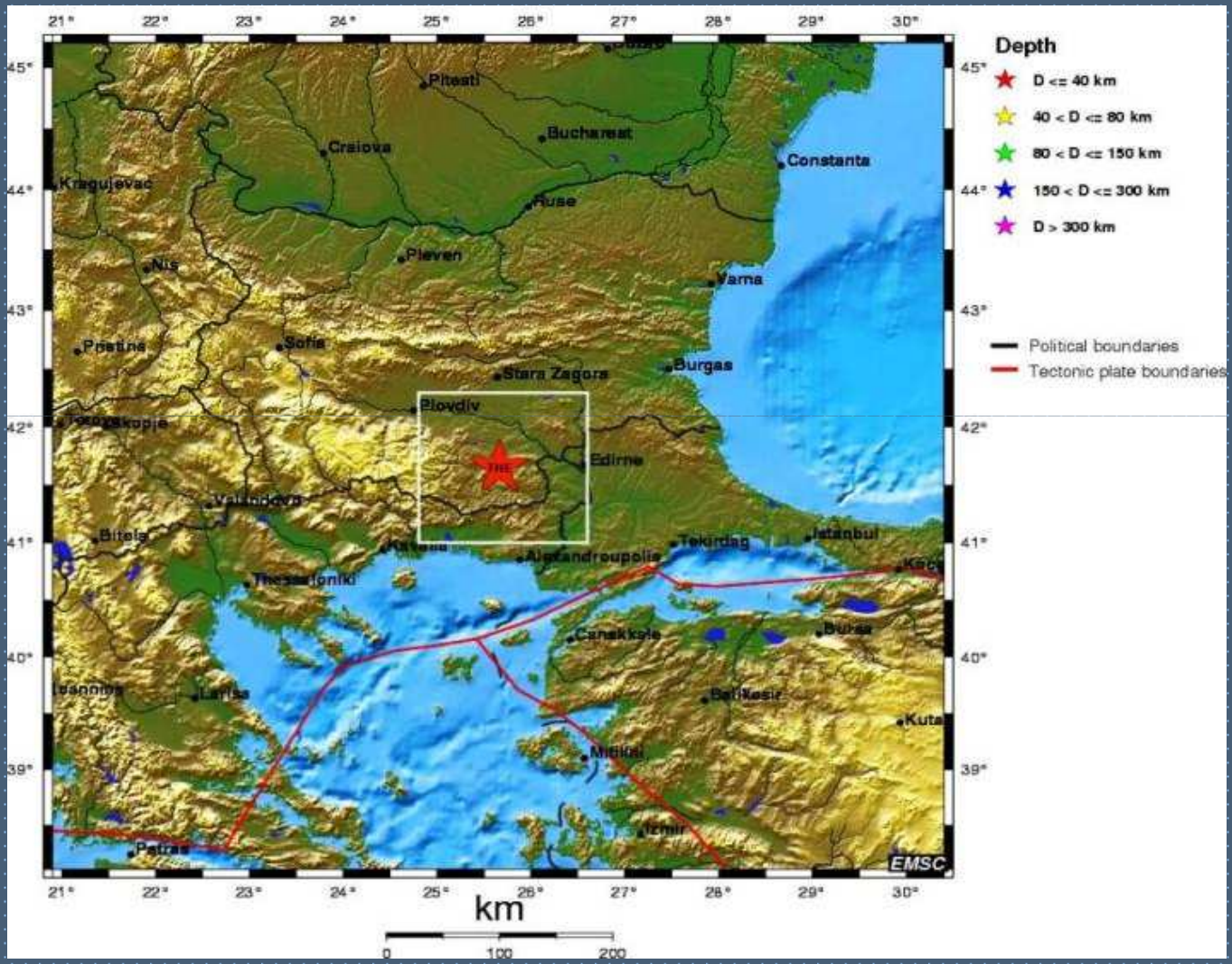
The National Digital Network (DN) for SGM monitoring in 2005



Process of calibration, testing, configuration and set-up of a new unit of the DN

Typical installation
ETNA 4498 (Krupnik station) SW Bulgaria

Kardjali EQ on the map of the Balkans

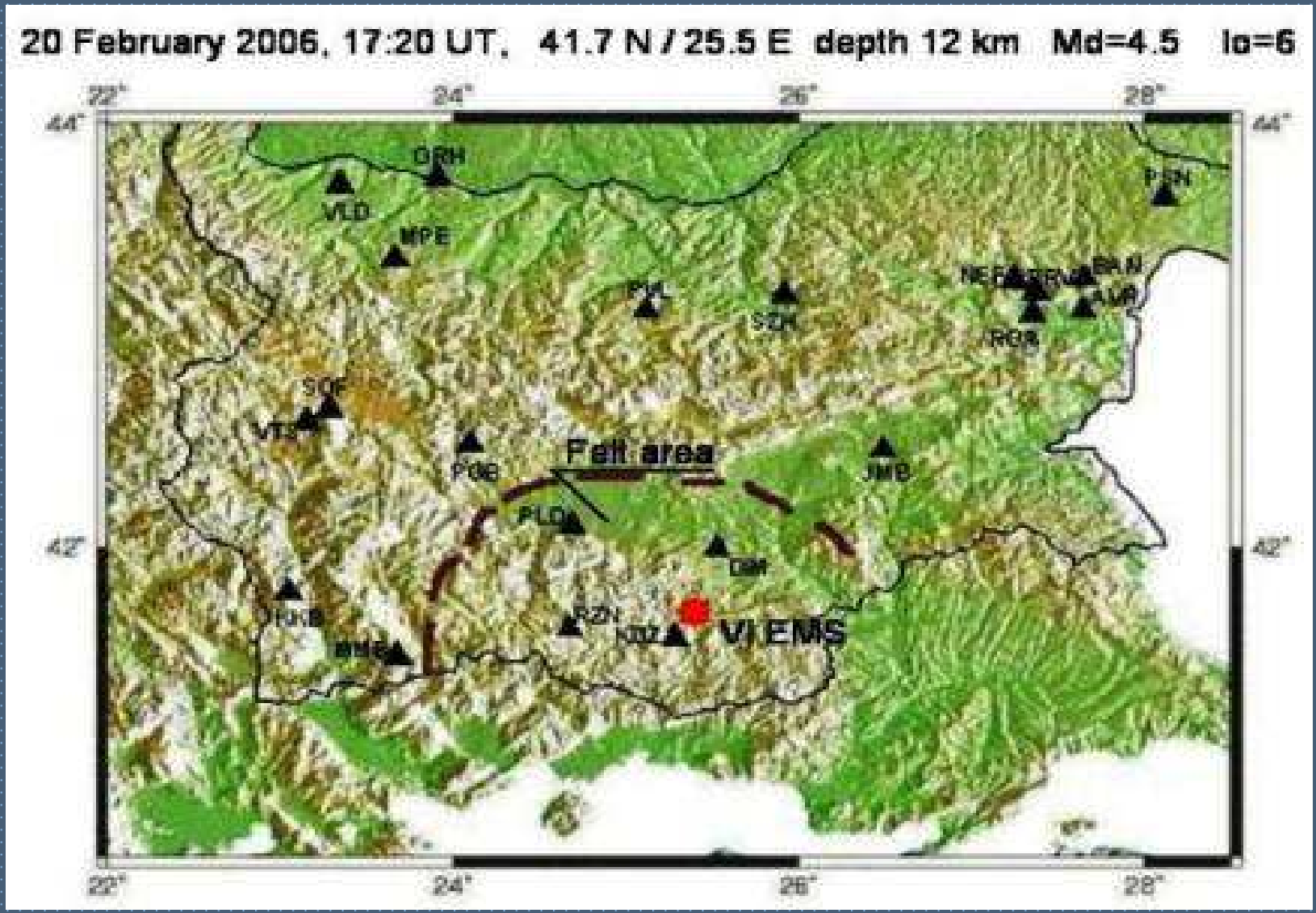


KARDJALI EARTHQUAKE

DATE	February 20, 2006
TIME (GMT)	17:20
EPICENTRAL LATITUDE	41.69° N
EPICENTRAL LONGITUDE	25.48° E
HYPOCENTRAL DEPTH	12 km
MAGNITUDE (M)	4.5
EPICENTRAL INTENSITY (EMS-98)	VI

Last EQ of similar strength - at the same location on August 28, 1936

Kardjali EQ on the map of Bulgaria



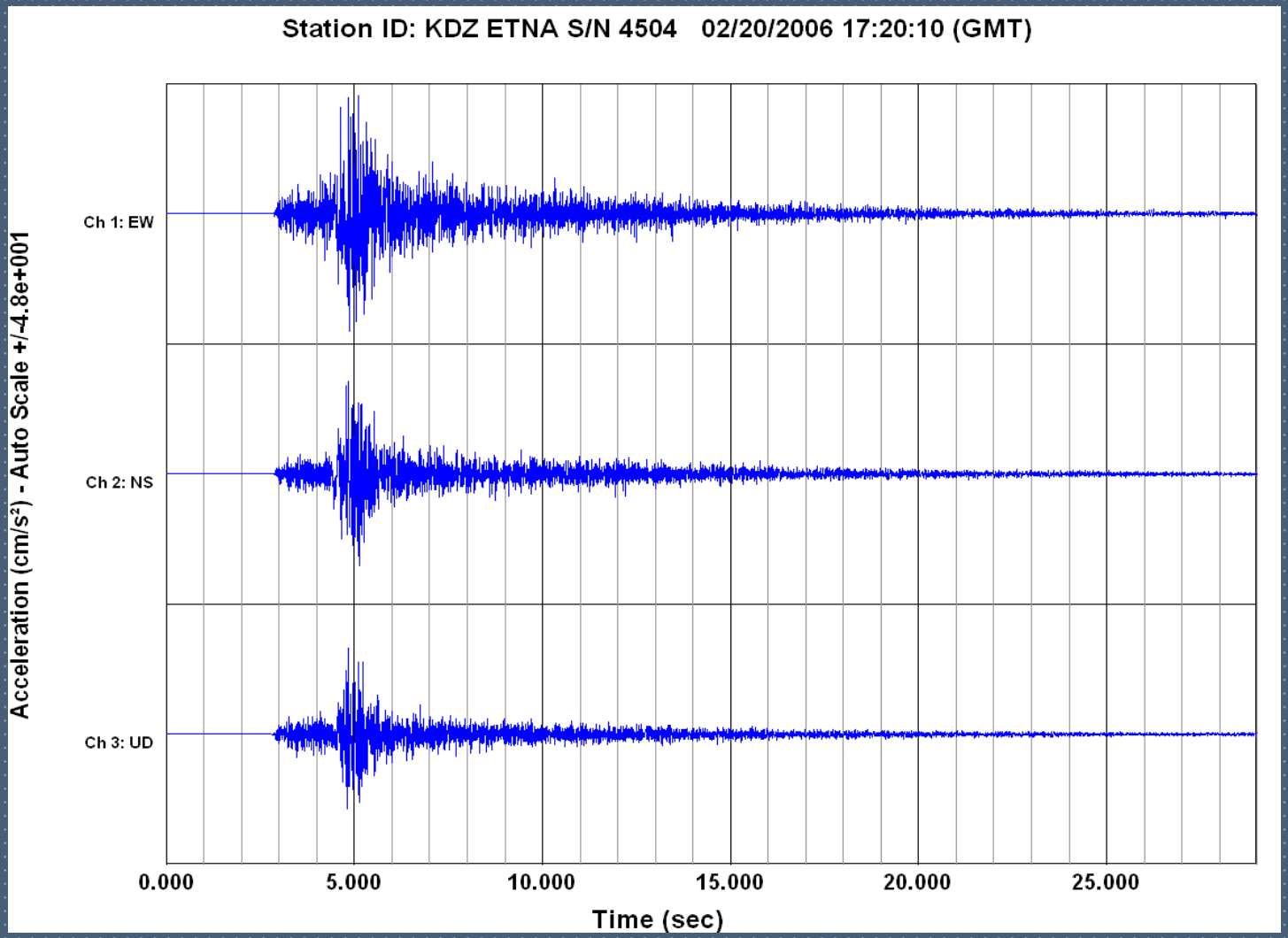
Time domain and spectral characteristics of the earthquakes in the region of Kardjali

Seismic equipment at the Kardjali station (KDZ).

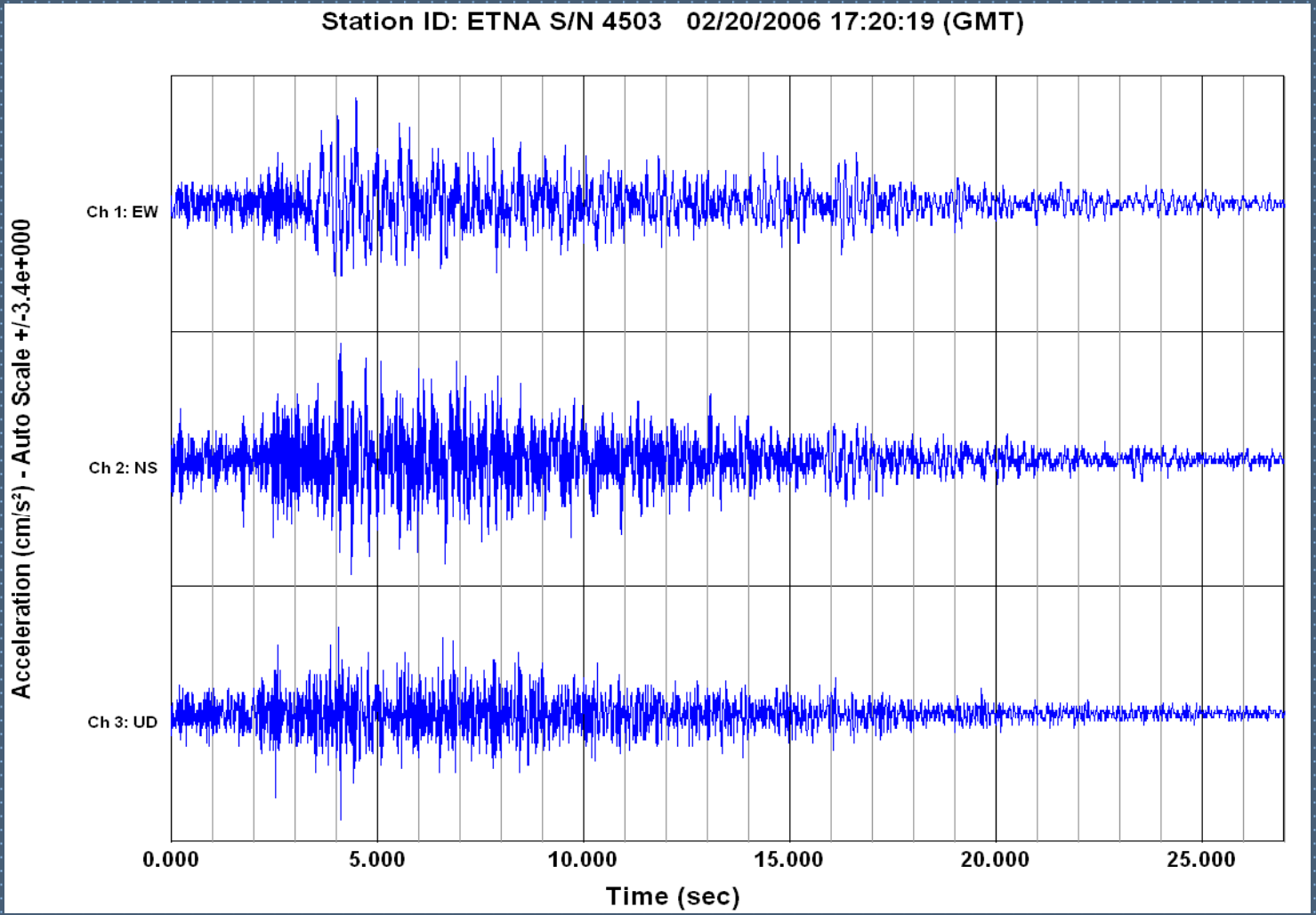
Seismic equipment at the Dimitrovgrad station (DIM).

Maximum accelerations a_{max} [cm/s^2] of the seismic events in the region of Kardjali during February and March, 2006.

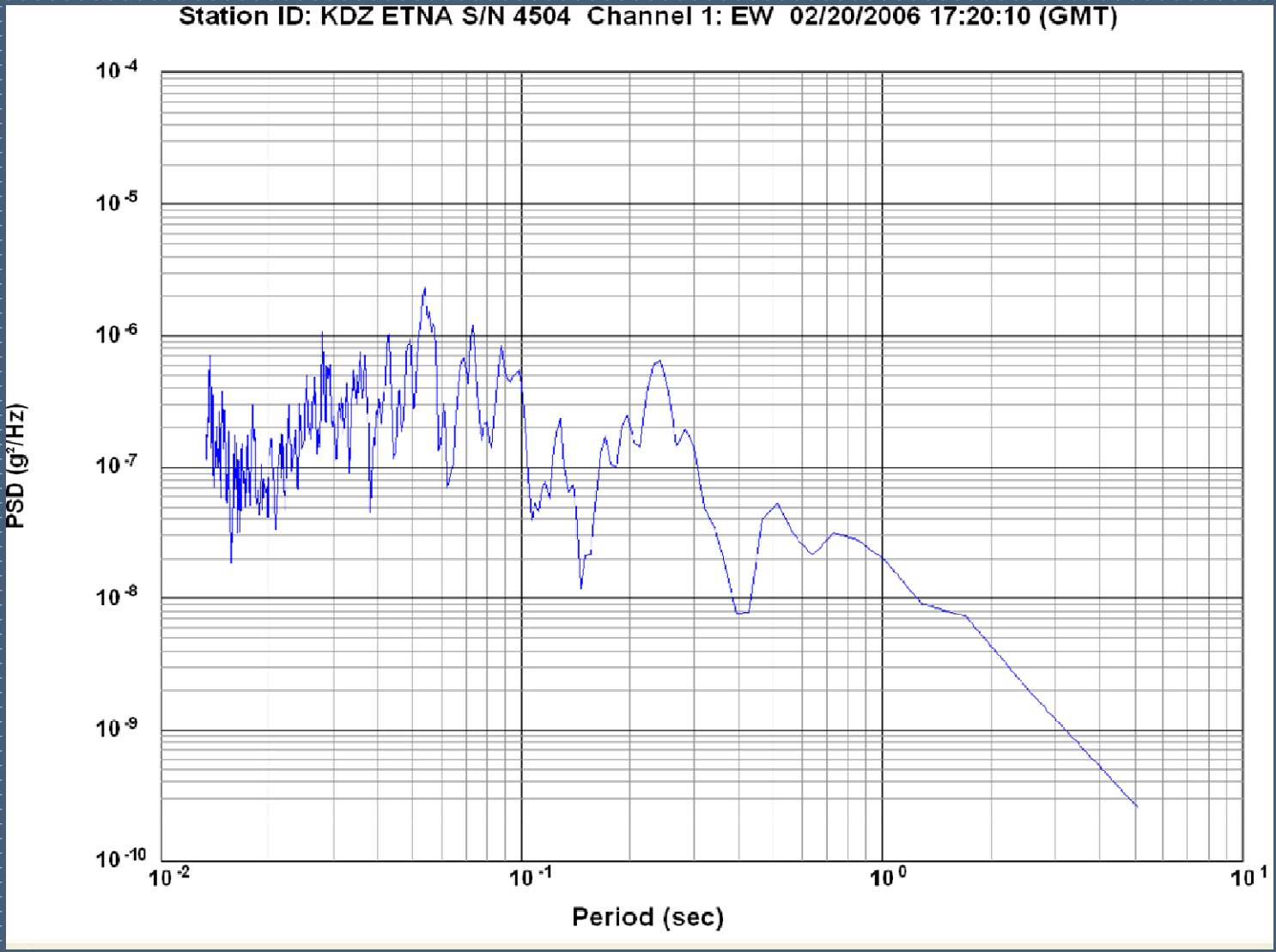
Station	Date (HH:MM)	1 Ch., E-W	2 Ch., N-S	3 Ch., U-D
KDZ	20.02. (17:20)	-38.03	-29.65	-30.70
DIM	20.02. (17:20)	2.83	2.97	-2.86
KDZ	20.02. (17:43)	-2.62	1.92	-1.24
KDZ	20.02. (18:29)	2.85	-2.14	2.09
KDZ	21.02. (15:21)	8.14	-6.23	-4.38
KDZ	22.02. (11:37)	-1.79	1.72	1.34
KDZ	24.02. (10:36)	-4.28	2.55	-4.00
KDZ	24.02. (13:35)	3.47	3.15	2.09
KDZ	14.03. (08:06)	5.29	5.80	-3.42
KDZ	14.03. (08:39)	-5.58	6.03	3.76



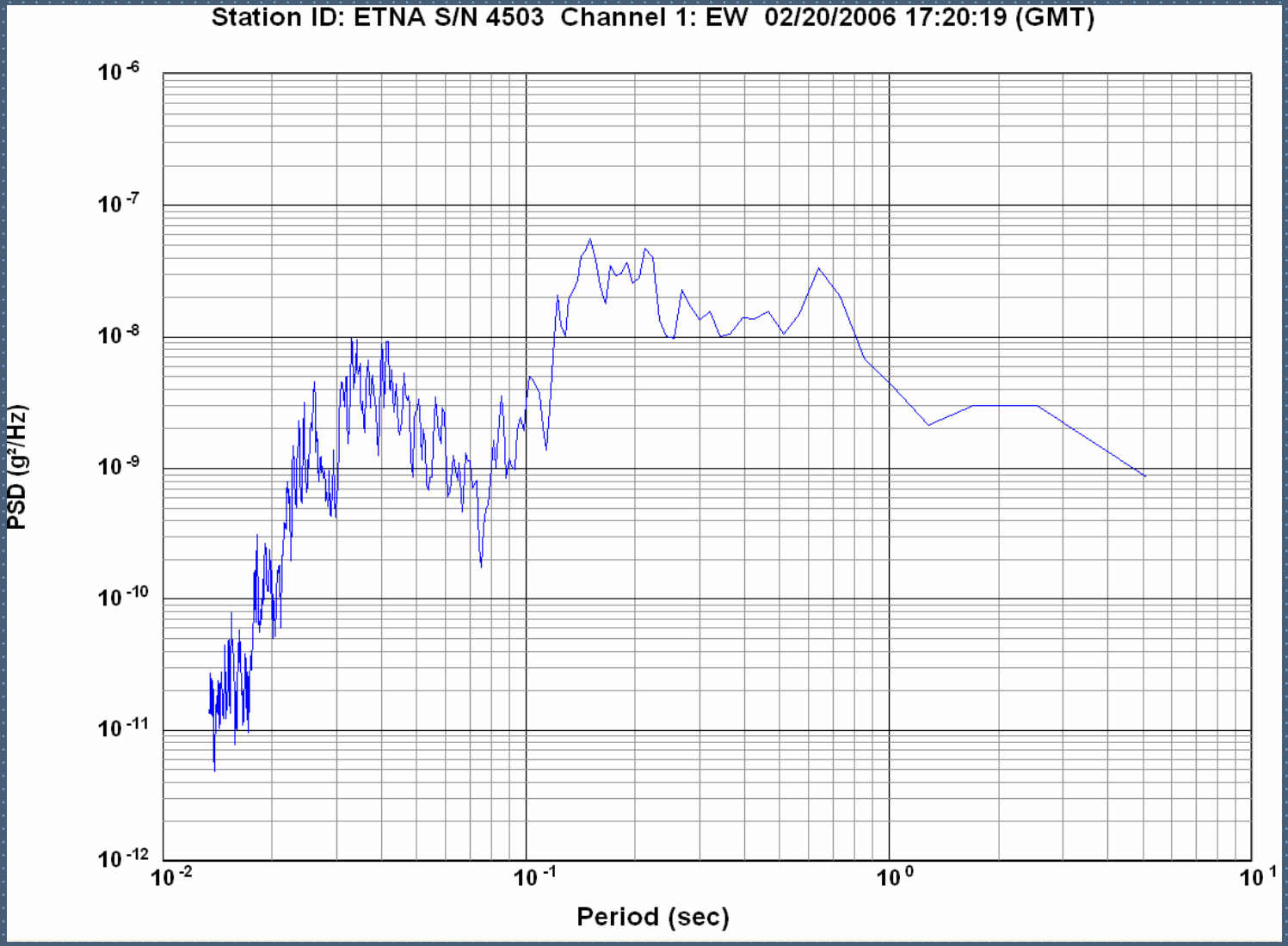
Kardjali station – 3D accelerogram /record of the DN/



Dimitrovgrad station – 3D accelerogram /record of the DN/

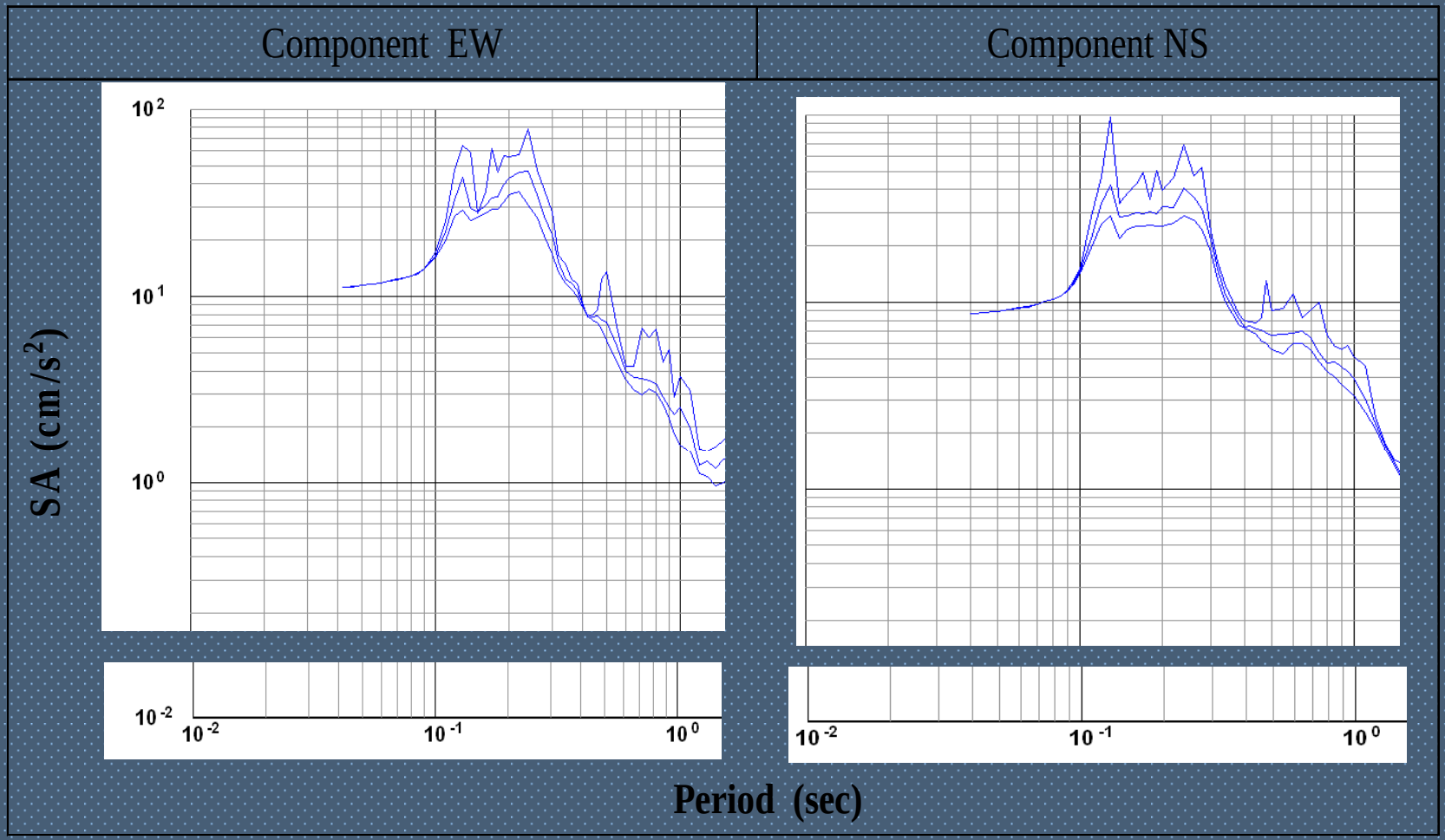


Power Spectral Density of the EW component /KDZ record of the DN/



Power Spectral Density of the EW component /DIM record of the DN/

EW **NS**



Acceleration Response Spectra for 0%, 2% and 5% damping /for KDZ accelerogram of the Kardjali Feb. 20, 2006 EQ/

Present National Digital Network for SGM monitoring

wth Computer Center for Observation and Data Management (CODM)

The Digital Network of the SMS

Station Provadia - ETNA # 4507

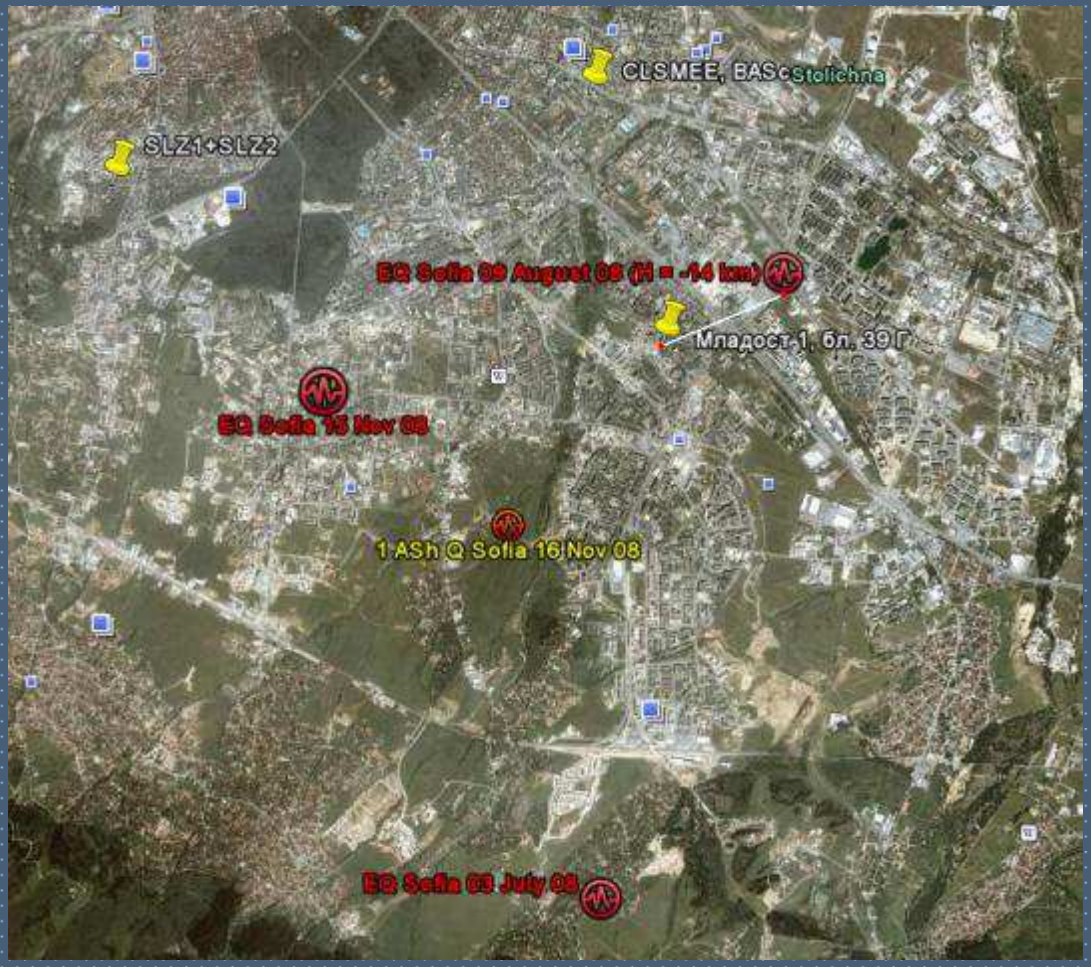
Recorded EQ in 2008 by the National SGM Network

Recorded 11 earthquakes with M < 4.4

2008 EQ #	Date (DMY)	Time UT (H:M:S)	Epicenter	Magn. (Md)	Intens. (Imax-EMS)	Hypocenter			Recorded by station
						Long. (E)	Lat. (N)	Depth [km]	
1	25/01/08	10:10:30	NE of Nova Zagora	2.7	III	26.12	42.51	15	JMB
2	29/01/08	05:29:35	Strajitza	2.7	IV	25.99	43.28	5	SZN
3	24/03/08	12:46:48	SE of Blagoevgrad	3.4	IV	23.25	41.98	2	KKB
4	15/04/08	03:43:10	Gabrovsko	4.2	V	25.37	42.90	9	SZN
5	12/05/08	10:11:55	Strajitza	4.3	VI	26.05	43.25	11	SZN, JMB
6	03/07/08	12:12:21	Sofia	3.1	IV	23.37	42.61	9	SGFI, SMLD
7	09/08/08	03:25:45	Sofia	3.3	III	23.39	42.66	14	SGFI, SMLD
8	05/11/08	07:36:54	Provadia	3.9	VI	27.46	43.16	9	PRV
9	15/11/08	20:08:19	Sofia	3.7	V	23.34	42.65	10	SGFI, SMLD, PLN
10	16/11/08	05:03:04	Sofia Aftershock	3.2	IV	23.36	42.64	10	SGFI, SMLD
11	18/11/08	08:17:11	Sofia Aftershock	2.3	III-IV	23.34	42.65	7.6	SGFI, SMLD

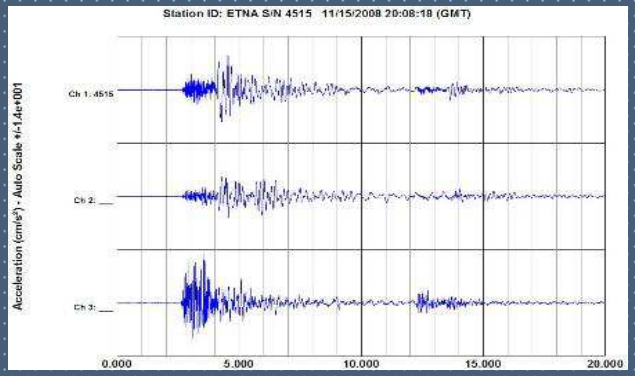
2008 Earthquakes recorded in Sofia

4 earthquakes with 3.0 < M < 3.8

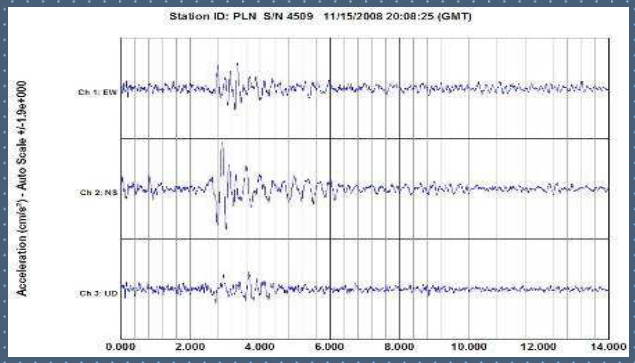


Map of 2008 Sofia EQs' epicenters

SGFI station



PLN station



3-D accelerograms of
15 November Sofia EQ

2008 List of processed Strong Motion Data (in Sofia)

2008 EQ	Station		Dist.	Axis	A0 peak	Predom. Freq.	Amax	Vmax	Dmax	SAmax (β = 5%)
#	code	cond.	[km]	code	[g]	[Hz]	[cm/s^2]	[cm/s]	[cm]	[cm/s^2]
6A	SGFI	base	7.34	EW NS V	0.005 -0.009 -0.011	2.3 ÷ 7.3 3.6 ÷ 7.3 2.5 ÷ 16.	5.38 -8.84 -10.43	-0.186 0.281 -0.127	-0.012 0.019 0.004	11.18 20.33 28.34
6B	SMLD	base	5.11	EW NS V	0.007 0.008 0.007	3.8 ÷ 5.4 3.7 ÷ 6.0 6.3 ÷ 9.5	7.22 7.38 7.01	-0.259 0.319 0.155	-0.018 0.021 -0.006	18.78 24.66 22.25
7A	SGFI	base	2.50	EW NS V	-0.002 -0.001 -0.003	4.7 ÷ 6.7 4.7 ÷ 6.7 5.6 ÷ 22.	-1.63 -0.97 -1.68	0.051 0.024 -0.017	0.004 0.002 -0.001	4.82 2.92 7.34
7B	SMLD	base	1.19	EW NS V	0.001 0.002 0.001	4.1 ÷ 9.7 4.0 ÷ 7.0 3.2 ÷ 11.	0.86 2.35 1.38	0.028 0.072 -0.023	0.001 -0.005 -0.001	2.79 6.15 4.26
9A	SGFI	base	4.20	EW NS V	0.009 -0.006 0.013	4.6 ÷ 7.3 5.0 ÷ 7.0 5.2 ÷ 21.	8.72 -5.35 10.08	-0.447 -0.284 0.173	-0.039 0.028 -0.012	35.63 26.72 51.23
9B	SMLD	base	3.39	EW NS V	0.006 0.007 -0.010	2.1 ÷ 8.1 1.3 ÷ 8.0 6.0 ÷ 9.1	5.91 6.54 -9.18	0.233 0.392 0.186	0.019 -0.044 0.012	20.24 23.81 29.89
9C	PLN	rock	20.37	EW NS V	0.001 0.002 0.001	5.0 ÷ 5.5 1.7 ÷ 5.6 2.2 ÷ 4.8	0.95 1.72 0.65	-0.031 -0.081 -0.027	-0.002 -0.005 0.004	3.93 5.87 2.18
10A	SGFI	base	4.08	EW NS V	-0.007 -0.006 0.011	4.4 ÷ 6.0 5.2 ÷ 6.1 10. ÷ 22.	-6.59 -5.37 10.21	0.197 -0.116 0.123	0.011 -0.005 -0.004	22.48 18.10 39.79
10B	SMLD	base	2.22	EW NS V	-0.007 0.004 -0.004	4.0 ÷ 8.2 4.2 ÷ 7.0 5.2 ÷ 9.0	-6.79 3.96 -4.31	0.196 -0.170 0.106	0.011 -0.012 0.002	17.21 16.79 17.48

2008 List of Strong Motion Data (in the country)

Processed 6 earthquakes with 2.7 < M < 4.4

2008 EQ	Stat.	Dist.	Axis	Predom. Freq.	Amax	Vmax	Dmax	SAmax (β = 5%)
#	code	[km]	code	[Hz]	[cm/s^2]	[cm/s]	[cm]	[cm/s^2]
1	JMB	33.70	EW	9.0 ÷ 10.	1.27	0.023	0.001	8.02
			NS	4.4 ÷ 12.	2.27	-0.069	0.002	7.03
			V	9.3 ÷ 11.	1.14	0.022	0.002	6.01
2	SZN	1.97	EW	4.0 ÷ 5.1	-9.70	-0.182	0.011	17.71
			NS	2.7 ÷ 5.0	-10.48	0.289	0.015	32.81
			V	8.0 ÷ 33.	6.86	-0.073	0.004	15.90
3	KKB	18.35	EW	3.8 ÷ 4.4	1.98	-0.050	-0.002	8.60
			NS	3.7 ÷ 4.6	1.98	-0.064	0.003	7.34
			V	9.2 ÷ 11.	1.87	0.030	-0.002	7.61
4	SZN	63.83	EW	3.6 ÷ 6.4	4.62	-0.165	-0.013	23.61
			NS	3.0 ÷ 5.6	-5.19	0.188	-0.012	25.43
			V	2.3 ÷ 8.0	-1.28	-0.043	0.004	5.84
5	SZN	6.21	EW	2.4 ÷ 7.4	-47.00	-1.382	0.110	122.00
			NS	3.3 ÷ 5.1	68.36	1.893	-0.129	208.69
			V	5.1 ÷ 14.	-24.36	0.403	-0.025	72.97
8	PRV	5.55	EW	7.3 ÷ 11.	13.05	-0.263	0.035	43.41
			NS	1.0 ÷ 20.	-17.71	-0.638	0.055	62.20
			V	1.1 ÷ 2.8	16.16	-0.474	-0.049	57.53

Power Spectral Density

Acceleration Spectra

Recorded EQ in 2010 by the National SGM Network

Recorded 3 earthquakes with 3.1 < M < 4.6

2010 EQ #	Date (DMY)	Time UTC (H:M:S)	Epicenter	Magn. (ML)	Intens. (Imax-EMS)	Hypocenter			Recorded by station
						Long. (E)	Lat. (N)	Depth [km]	
101	27/04/10	15:11:26	S of Sofia	3.2	-	23.24	42.49	10	SGFI VTS
102	10/09/10	07:11:44	SE of Sofia	3.5	V	23.30	42.66	2	SGFI SMLD IKR1
103	07/10/10	19:51:22	SE Provadia	4.5	-	27.55	43.13	2	PRV

2010 List of processed Strong Motion Data (in Sofia)

2010 EQ	Station		Dist.	Axis	A0 peak	Predom. Freq.	Amax	Vmax	Dmax	SAmax (β = 5%)
#	code	cond.	[km]	code	[g]	[Hz]	[cm/s^2]	[cm/s]	[cm]	[cm/s^2]
101A	SGFI	base	22.30	EW NS V	-0.002 -0.001 -0.001	2.6 ÷ 7.6 4.2 ÷ 7.7 6.6 ÷ 7.7	-1.78 -0.82 -0.62	0.050 -0.026 0.011	0.003 0.002 0.001	3.75 2.86 2.49
101B	VTS	rock	13.80	EW NS V	-0.031 -0.047 -0.011	10. ÷ 12. 10. ÷ 12. 10. ÷ 12.	-2.17 2.32 -2.39	-0.043 0.036 -0.042	-0.002 -0.003 -0.002	7.36 7.14 7.11
102A	SGFI	base	5.92	EW NS V	-0.026 0.017 0.020	3.4 ÷ 6.5 4.2 ÷ 6.1 4.0 ÷ 22.	-25.99 16.47 -17.58	-0.854 0.327 -0.270	0.052 -0.015 0.012	97.17 55.51 80.63
102B	SML D	base	6.30	EW NS V	-0.020 0.016 -0.014	3.3 ÷ 8.0 4.1 ÷ 5.2 5.5 ÷ 7.2	-19.25 15.90 -13.29	0.704 -0.746 -0.328	0.043 -0.052 -0.013	47.78 56.98 75.60
102C	IKR1	Iskar Dam Wall	25.20	EW NS V	0.003 0.006 0.001	8.0 ÷ 23. 5.0 ÷ 15. 5.3 ÷ 24.	2.38 5.63 1.11	-0.034 -0.117 0.028	-0.002 -0.004 0.002	9.12 21.94 4.05
103A	PRV	rock	11.75	EW NS V	-0.033 -0.024 -0.029	4.5 ÷ 17. 7.0 ÷ 19. 8.0 ÷ 12.	-30.85 -24.39 -26.29	-0.651 0.433 -0.549	0.123 -0.061 -0.060	99.77 112.00 99.09

Recorded EQ in 2012 by the National SGM Network

Recorded 7 earthquakes with M > 4 and 32 with M > 3

(Recorded EQ in 2011: only 1 with M = 4 and 6 with M > 3)

2012 EQ #	Date (DMY)	Time UTC (H:M:S)	Epicenter	Magn. (Mw)	Intens. (Imax-EMS)	Hypocenter			Recorded by Sofia stations
						Long. (E)	Lat. (N)	Depth [km]	
122	22/05/12	00:00:33	W of Sofia	**5.6**	VIII	23.01	42.66	10	SGFI SGL1 VTS
124	22/05/12	01:30:51	W of Sofia	4.7	VI	23.05	42.64	10	SGFI SGL1 VTS

May 22, 2012 Pernik Earthquake

00:00:33.5 UTC,

(42.58°N, 23.00°E),

Ms = 5.8 (Mw = 5.6),

H = 10 km,

I = VII- VIII (EMS)

Same day: 29 Aftershocks, 6 of which felt in Sofia!

10 days after: 650 ASh in the epicentral zone (most with Mw < 3.0)

Strongest aftershock: Mw = 4.7

4 aftershocks with Mw > 4.0; 5 aftershocks with Mw > 3.5;

12 aftershocks Mw > 3.0.

2012 Pernik Earthquake recorded in Sofia

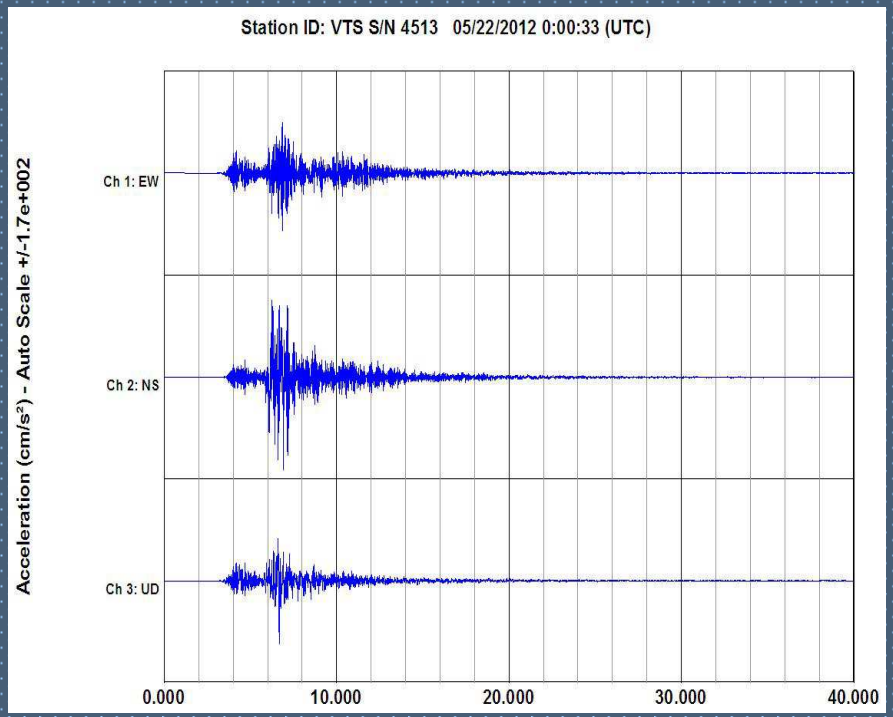
EQ epicenter to VTS, SBO, SGFI stations that recorded it

Earthquake engineering relevant characteristics evaluated at Sofia stations for the seismic impact of May 22, 2012 Pernik earthquake

Record	Station		Epicenter distance	Axis code	A max	SAmax (β = 5%)	Predom. Freq.	Order of PSD
#	Code	Cond.	[km]		[cm/s^2]	[cm/s^2]	[Hz]	[g^2/Hz]
1	VTS	rock	19.00	EW NS V	- 96.22 - 156.47 - 105.97	98.67 190.24 210.30	2.0 ÷ 5.2 1.3 ÷ 4.2 2.4 ÷ 8.3	< 1. 10^{-4}
2	SGL1	base-ment	26.00	EW NS V	42.62 30.26 21.94	103.6 81.8 66.3	0.5 ÷ 0.8 0.4 ÷ 0.8 0.8 ÷ 1.8	< 3. 10^{-5}
3	SGFI	base-ment	29.60	EW NS V	38.33 - 29.91 - 17.81	112.7 114.1 53.3	0.4 ÷ 0.8 0.4 ÷ 0.9 0.5 ÷ 1.1	< 4. 10^{-5}

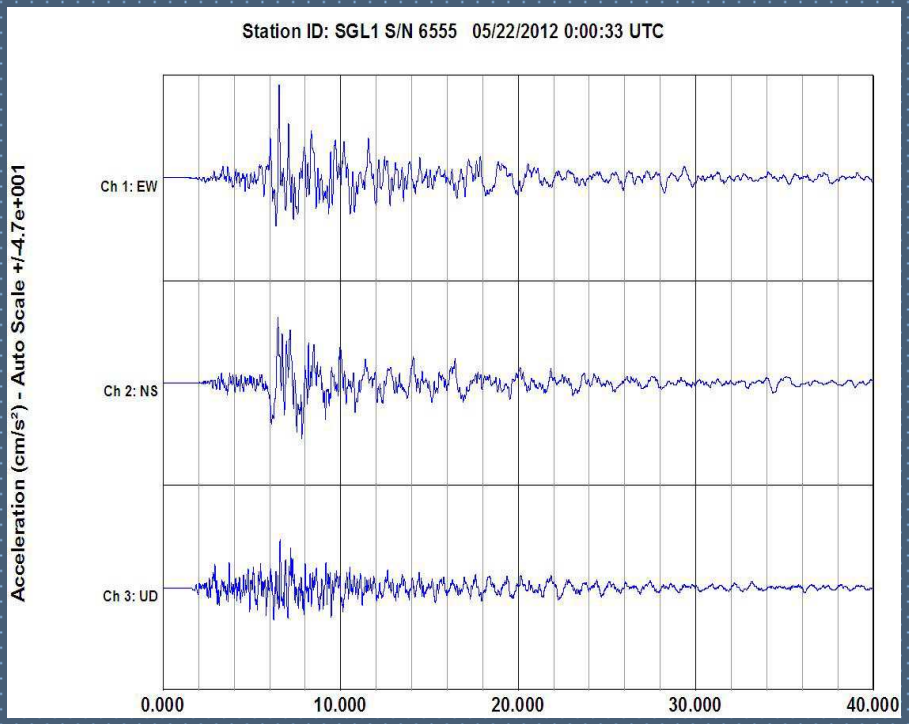
Corrected accelerograms

VTS station



19 km

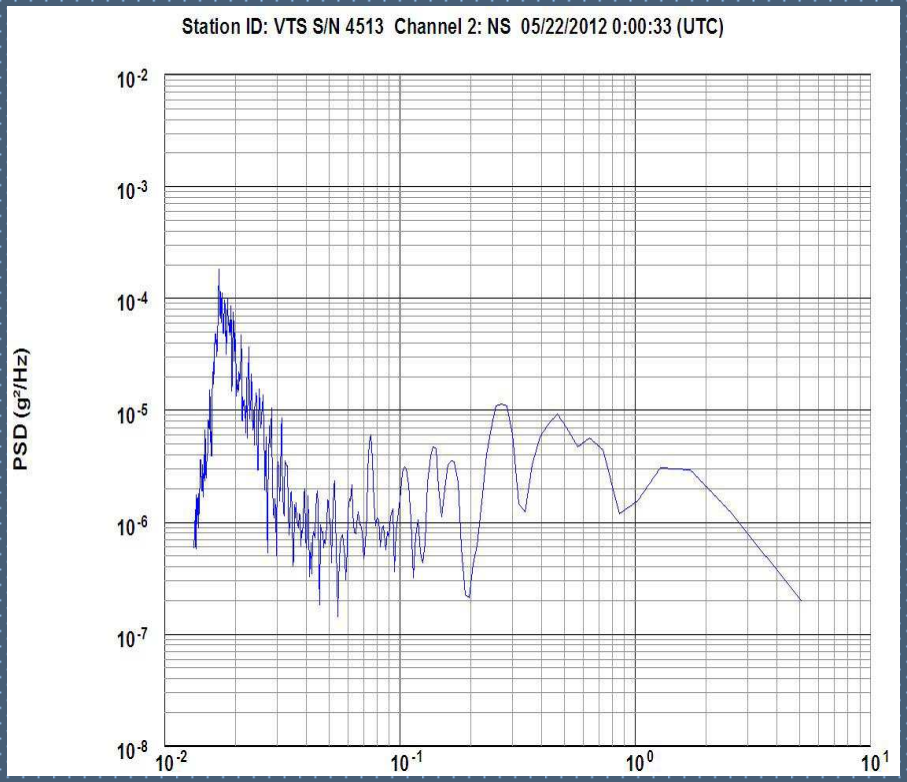
SGL1 station



26 km

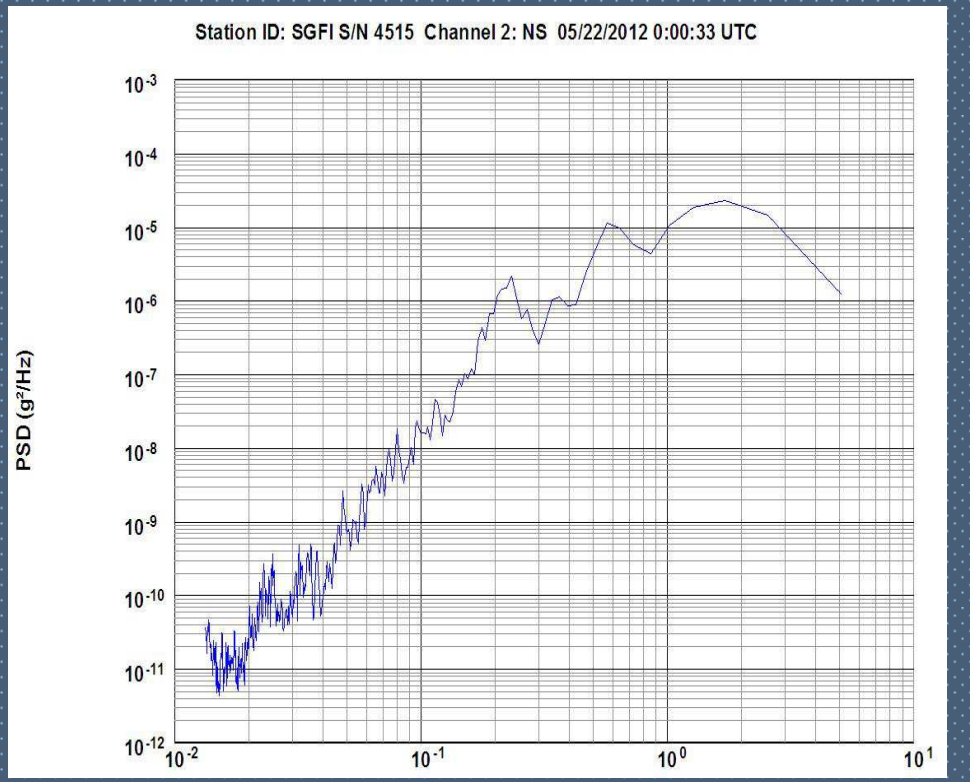
Power spectral densities

VTS station



19 km

SGFI station

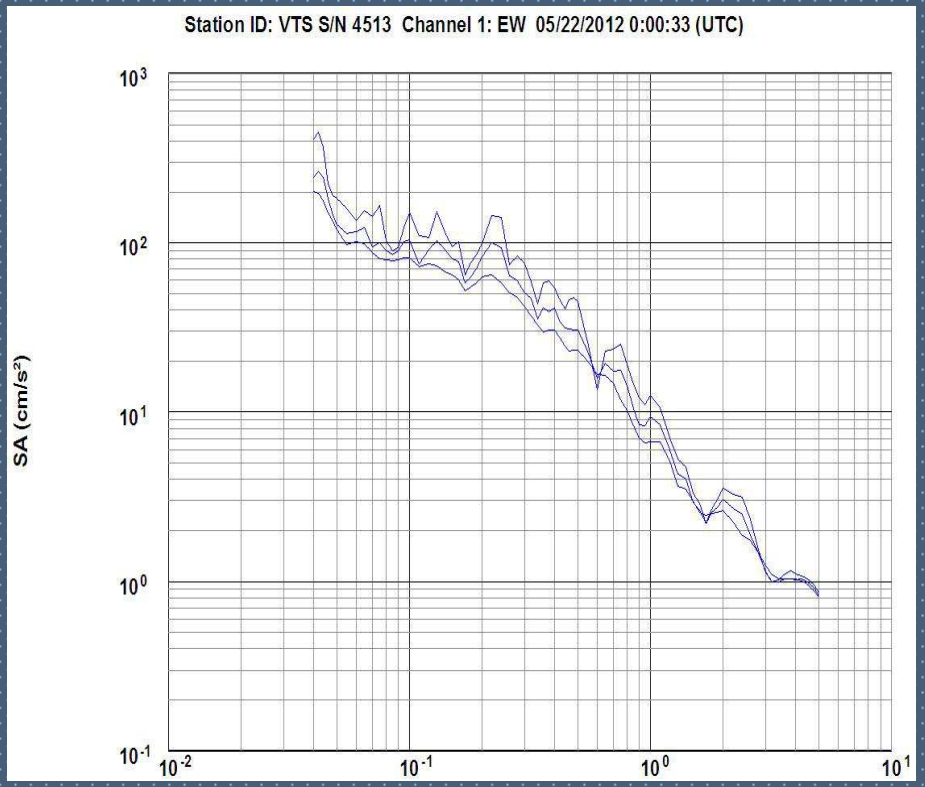


29.6 km

Acceleration Response Spectra for 2, 5 and 10% damping

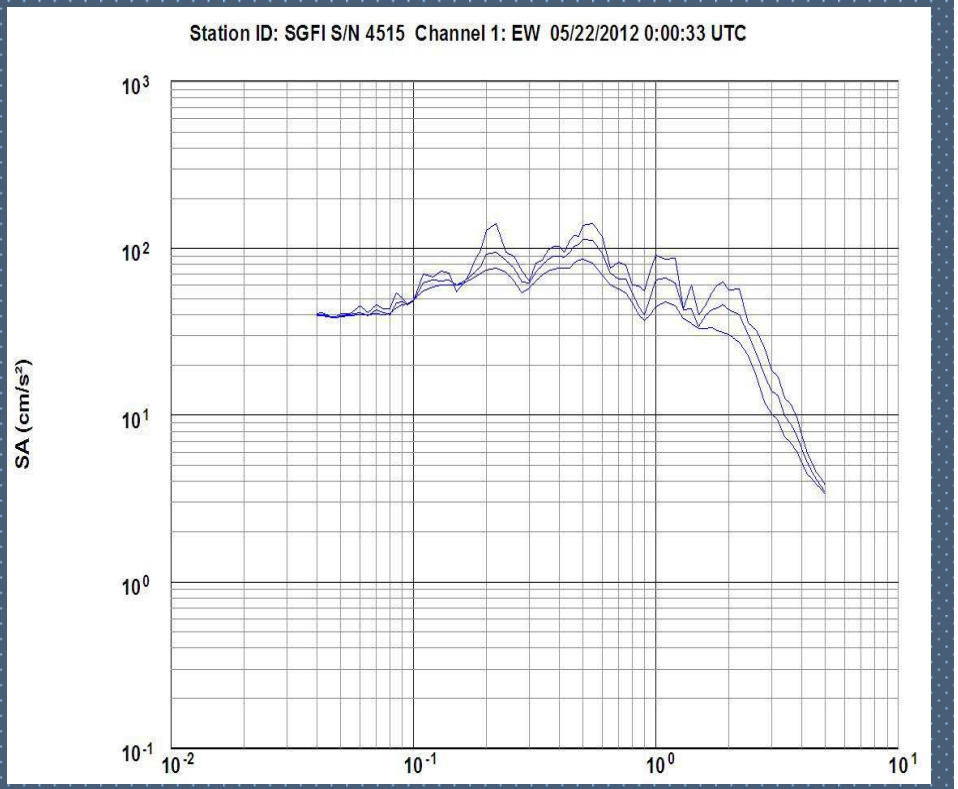
EW components

VTS station



19 km

SGFI station

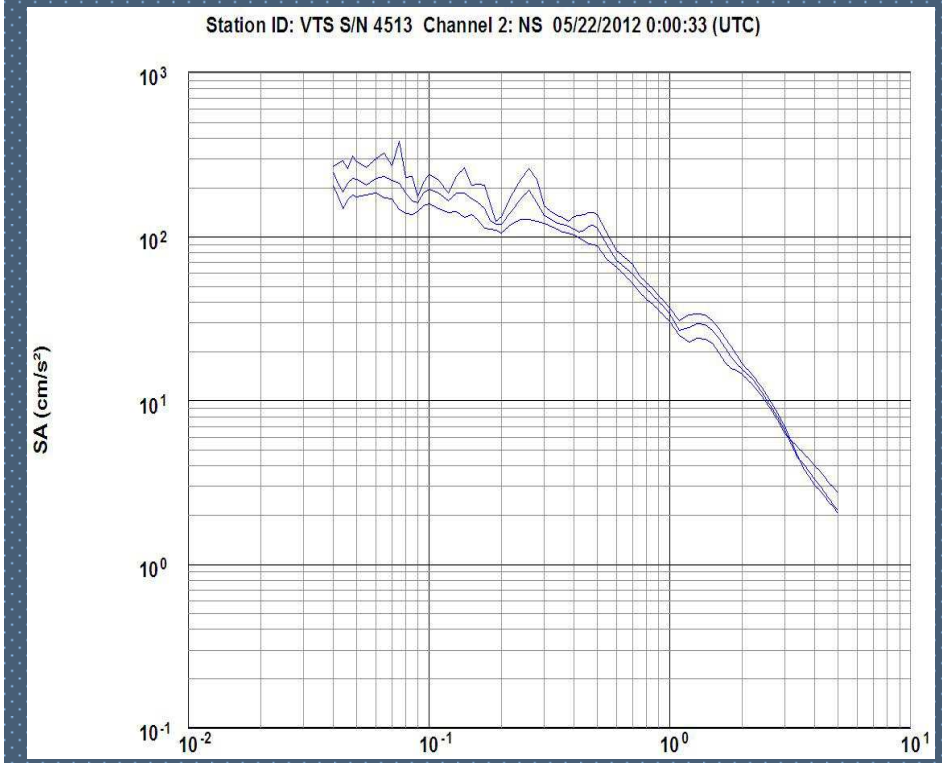


29.6 km

Acceleration Response Spectra for 2, 5 and 10% damping

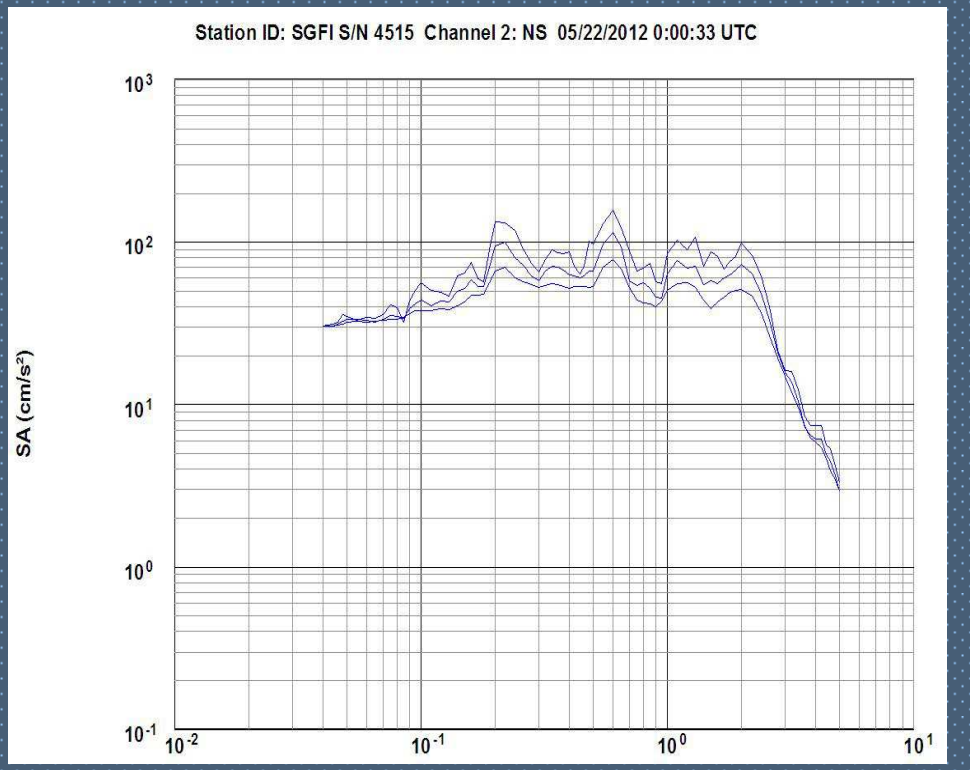
NS components

VTS station



19 km

SGFI station



29.6 km