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REGIONAL MAGNITUDE RELATIONS FOR THE BALKAN PENINSULA

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Ренета Райкова, Мария Филипова, Милен Цеков. РЕГИОНАЛНИ МАГНИТУДНИ ЗАВИСИМОСТИ ЗА БАЛКАНСКИЯ ПОЛУОСТРОВ

Виртуалната сеизмична мрежа на Софийския университет (ВСМСУ) е основана през 2015 г. в рамките на научен проект, финансиран от Софийския университет „Св. Климент Охридски“. ВСМСУ се състои от 16 сеизмични станции от различни национални и международни мрежи в Югоизточна Европа със свободен достъп до данните в реално време. Получихме стойности за няколко вида магнитуди (M_l, M_d, M_b, M_S), анализирайки 25 земетресения в района на Балканския полуостров чрез измерване на максималната амплитуда и нейния период за определени сеизмични вълнови пакети, както и на продължителността на земетръсните записи. Приложихме множествен линеен регресионен анализ за получаване на седем магнитудни зависимости, специфични за района на Балканския полуостров.

Reneta Raykova, Maria Filipova, Milen Tsekov. REGIONAL MAGNITUDE RELATIONS FOR THE BALKAN PENINSULA

The Virtual Seismic Network of Sofia University (VSNSU) was established in 2015 as a part of a scientific research project funded by Sofia University "St. Kliment Ohridski". VSNSU consists of sixteen seismic stations belonging to several national and international networks in southeastern Europe with open access to near real-time data. We estimated values for several magnitude types (M_l, M_d, M_b, M_S) analyzing 25 earthquakes in the Balkan Peninsula region by measuring the maximum amplitude

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and its period for certain seismic waves, as well as the earthquake's duration. We applied multiple linear regression method to obtain seven magnitude relations, specific for the Balkan Peninsula region.

Keywords: earthquakes, seismograms, magnitude, Balkan Peninsula
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1. INTRODUCTION

The magnitude gives an estimate of the energy release during an earthquake. It is one of the most important earthquake parameters. Various magnitude types use different features of a seismogram record to characterize earthquake size. The magnitude estimates of a given seismic event obtained by the seismogram records from different stations may differ, because of the radiation pattern of respective seismic waves, differences in the Earth's structure between the hypocentral zone and the corresponding seismic stations, the quality of the records, etc. The magnitudes reported by different seismic agencies for specific earthquake may also vary significantly, even by more than one magnitude unit [1].

The Balkan Peninsula is one of the most seismically active regions in Europe. However, a homogenized catalog of modern earthquake activity in the region does not exist. Different national seismic agencies report magnitudes based on different network specific calibrations. Thus, the magnitude estimates for individual Balkan Peninsula's earthquakes reported by different national seismic networks, generally differ. There are two approaches to construct magnitude homogenized seismic event databases: (1) using general orthogonal regression (or other proper regression) method to calculate regression relations between the differing network magnitude scales, or (2) using original seismogram records from stations belonging to different seismic network and a reference magnitude scale to construct new magnitude relations. In this work we follow the second approach and constructed Balkan Peninsula specific magnitude relations based on seismic records from the Virtual Seismic Network of Sofia University (VSNSU) and magnitude estimates from IDC [2] as reference values in the calibration procedure. In a previous study [3] 490 individual measurements from seismic records of 11 earthquakes Balkan Peninsula earthquakes were used to calibrate 7 magnitude scales of 4 magnitude types (local magnitude M_l, duration magnitude M_d – 2 scales, body wave magnitude M_b – 2 scales, and surface wave magnitude M_S – 2 scales). Here, following the same procedure as in [3], we extend the number of measurements to 758 (measurements from seismograms of 25 Balkan Peninsula earthquakes, presented in [3] and [4]) in order to revise the specific for the region magnitude relations obtained in [3].

The structure of the paper is as follows. In Section 2 we present the data and procedures to obtain magnitude values for a given magnitude type and we commented on some peculiarities and problems in magnitude estimations. In Section 3 we describe the application of multiple linear regression analysis method to calculate magnitude relations specific for the Balkan Peninsula region from the available data. We compare our calibration relations with these obtained in [3] and with magnitude relations calibrated for other regions of the globe. In Section 4 we summarize our findings and we outline some future work to improve magnitude relations for the earthquakes in the Balkan Peninsula region.

2. MAGNITUDE MEASUREMENTS

Virtual Seismic Network of Sofia University (VSNSU) was established in 2015 as a part of a scientific project funded by Sofia University. The 16 VSNSU seismic stations cover relatively uniformly the Balkan Peninsula region and they have open access to their seismic records in near real time. Seismic records from twenty five earthquakes were analyzed in the studied region in order to obtain several magnitude relations specific for the Balkan Peninsula. Fig. 1 shows the location of the VSNSU seismic stations and the epicenters of the analyzed earthquakes. The procedure for magnitude calculations, based on the respective seismogram measurements, was explained in detail in [3] and [4]. Every seismic record was processed and converted to the simulated record of an instrument appropriate to measure relevant amplitudes and their periods for a specific magnitude. The duration of the earthquakes was measured from the unfiltered seismic records. An example for amplitude, period and duration measurements for different magnitudes is shown in Fig. 2. Magnitude relations calibrated by several authors for certain regions of the globe were used in [3] and [4] to calculate magnitude values from the measured parameters. Normally these calibrations are site specific and they may not be valid in other regions including the Balkan Peninsula.

Estimates for seven magnitudes of four magnitude types (M_d, M_l, M_S, M_b) were obtained by the same procedure described in [3] and [4] using seismograms of 25 earthquakes, located in the Balkan Peninsula region with magnitude ≥4.0 (as reported by [5]). Magnitudes were estimated for every seismic station that recorded a respective earthquake with sufficient quality. Next, we calculated the relevant event magnitudes (for each magnitude type) for each of 25 earthquakes by averaging station magnitude estimates. Thus we obtained the VSNSU magnitudes by "global" relations in order to compare them with regional magnitude estimates, defined in the next Section.

We identified some station magnitude estimates that are disproportionately higher or lower than the other station magnitude estimates for the same seismic event. This discrepancy may be explained by a combination of several factors. Firstly, this problem is related to the large uncertainty in the estimation of important earthquake parameters such as epicenter coordinates, hypocenter depth and origin time. The values of these parameters reported by different seismic agencies often vary significantly [1]. For example, for one of the selected events the variation in earthquake's depth reported by different seismic centers is comparable to the epicentral distance to the closest station. Secondly, the seismic waveforms are influenced also by seismic source peculiarities like the nature of rapture process. For example, if the rapture process is relatively slow or if it develops in several consecutive branches, the seismic wave amplitudes would be smaller and the record durations would be longer in respect to a "standard" earthquake. Thirdly, the quality of the magnitude estimates is affected by the seismic noise level, especially for seismic stations in immediate vicinity of coastal regions. Noisy records make difficult identification and measurement of important earthquake parameters such as amplitude, period and duration.

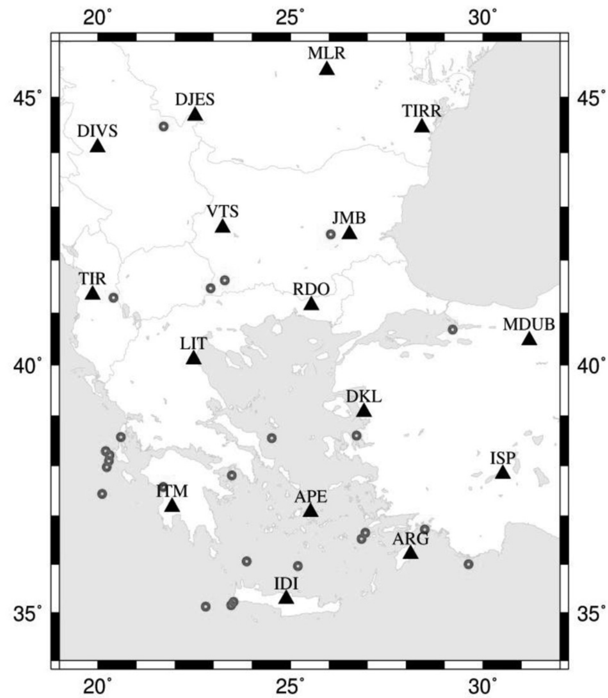

Fig. 1. Map of the Balkan Peninsula region with locations of the VSMSU seismic stations (black triangles) and the epicenters of the selected seismic events (red circles)

3. MAGNITUDE RELATIONS FOR THE BALKAN PENINSULA REGION

We used the multiple linear regression analysis method to obtain magnitude relations for each magnitude type that is specific to the Balkan Peninsula region. The multiple linear regression is a common statistical procedure used to find the relationship between a response variable and two or more explanatory variables by fitting a linear equation to observed data. It is applied to variety of statistical problems including for magnitude scale calibrations [6, 7]. We used the R free software environment [8] for statistical computations to implement the method.

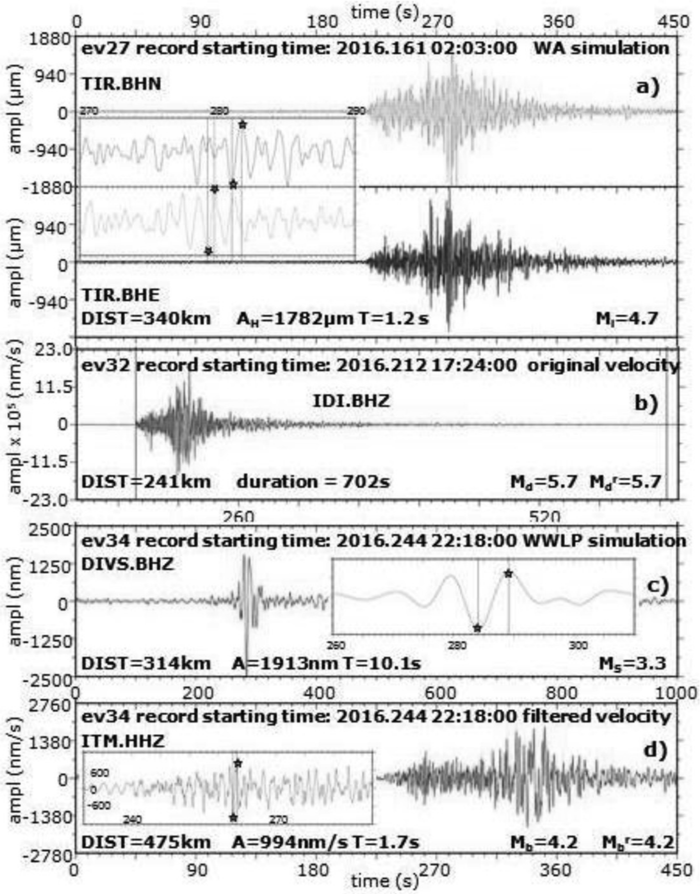

Fig. 2. Measurements to obtain magnitude estimates of different types: (a) for local magnitude M_l at station TIR; (b) for duration magnitudes M_d and M_d^r at station IDI; (c) for surface wave magnitudes M_S and M_{S_BB} at station DIVS; (d) for body wave magnitude M_b at station ITM

We applied multiple linear regression to the set of magnitude measurements reported in [3] and [4]. Thus, we determined the specific coefficients A_i, B_i, C_i and F_i in the generalized relations for M_d, M_l, M_S, and M_b:

$$M_l = A_1 \times \log(A_H) + B_1 \times \log(R) + C_1 \times R + F_1$$

$$M_b = A_2 \times \log(V) + B_2 \times \log(D) + F_2$$

$$M_b^r = A_3 \times \log(V) + B_3 \times \log(R) + F_3$$

$M_S = A_4 \times \log(A/T) + B_4 \times \log(\Delta) + F_4$
$M_{S\text{–}BB} = A_5 \times \log(V/2\pi) + B_5 \times \log(\Delta) + F_5$
$M_d = A_6 \times \log(\tau) + B_6 \times D + F_6$
$M_b^r = A_7 \times \log(\tau) + B_7 \times R + F_7.$

Here, A and A_H denote the relevant wave amplitudes in [μm] or [nm], T – period of the relevant amplitude in [s], V – amplitude of the velocity in the relevant seismic record in [m m/s], t – duration of the earthquake record in [s], R – hypocentral distance in [km], D – epicentral distance in [km], Δ – epicentral distance in [deg]. The sign "×" in the equations denotes multiplication. The difference between the two body wave magnitudes is that M_b uses epicentral distance while M_b^r – hypocentral distance. The difference between the two surface wave magnitudes is that M_S uses WWWLP instrument simulation while M_{S_BB} – the broad-band long-period filtered velocity records. The difference between the two duration magnitudes is that M_d uses epicentral distance while M_d^r – hypocentral distance. See [3] and [4] for more details about magnitudes definition.

We used the corresponding transformations of the relevant seismogram parameters (see the generalized relations above) as explanatory variables in the regressions. We adopted corresponding magnitudes obtained by IDC [2] (provided by ISC [1]) as reference values. Body wave magnitudes were calibrated with respect to reported by IDC M_b magnitude estimates, surface wave magnitudes were calibrated with respect to reported by IDC M_S magnitude estimates, while local and duration magnitudes were calibrated with respect to IDC M_l magnitude estimates. Reference magnitude values for each selected earthquake are listed in Table 1.

Table 1. Reference magnitudes obtained by IDC [2]. Event labels follow [3] and [4]

Event	M_l (IDC)	M_S (IDC)	M_b (IDC)	Event	M_l (IDC)	M_S (IDC)	M_b (IDC)
Ev01	4.0	3.4	4.2	Ev18	4.3	3.7	4.2
Ev02	4.2	3.6	4.5	Ev20	3.7	3.3	4.0
Ev03	-	-	3.7	Ev21	3.7	3.3	3.6
Ev04	-	3.8	4.2	Ev25	3.5	3.5	3.9
Ev05	4.0	3.2	3.8	Ev27	3.7	3.5	4.3
Ev06	4.4	4.7	4.8	Ev28	3.4	3.2	3.8
Ev07	4.0	2.9	3.6	Ev29	-	-	-
Ev08	3.6	3.1	3.9	Ev32	4.2	4.3	4.8
Ev09	3.8	3.3	4.1	Ev33	3.6	3.0	4.0
Ev11	4.3	3.9	4.4	Ev34	-	-	-
Ev14	3.9	3.4	3.8	Ev36	3.4	-	3.9
Ev15	-	4.8	4.8	Ev37	4.1	3.6	4.5
Ev17	-	3.8	4.0				

The number of waveforms used in the regression for the corresponding magnitude relations is summarized in Table 2. The number of waveforms used in [3] is presented for comparison.

Table 2. Number of waveforms used for calibration of specific magnitude scales

Magnitude scale	M_l	M_b	M_b^r	M_S	M_{S_BB}	M_d	M_d^r
Number of waveforms (this study)	94	132	131	142	144	56	59
Number of waveforms (in [3])	55	91	91	93	95	32	33

Applying the multiple linear regression method we obtained the following magnitude relations:

$$M_l = (0.14 \pm 0.14) \times \log(A_H) - (1.01 \pm 0.64) \times \log(R) + (0.0020 \pm 0.0009) \times R + (5.31 \pm 1.33)$$

$$M_b = (0.49 \pm 0.05) \times \log(V \log(1.08 \pm 0.12) \times \log(D) - (0.28 \pm 0.46)$$

$$M_b^r = (0.47 \pm 0.05) \times \log(V) + (1.10 \pm 0.13) \times \log(R) - (0.30 \pm 0.46)$$

$$M_S = (0.70 \pm 0.03) \times \log(A/T) + (0.55 \pm 0.11) \times \log(\Delta) + (1.74 \pm 0.11)$$

$$M_{S\_BB} = (0.71 \pm 0.03) \times \log(V/2\pi) + (0.53 \pm 0.11) \times \log(\Delta) + (1.72 \pm 0.11)$$

$$M_d = (0.37 \pm 0.16) \times \log(\tau) - (0.00032 \pm 0.00032) \times D + (3.05 \pm 0.41)$$

$$M_d^r = (0.36 \pm 0.17) \times \log(\tau) - (0.00026 \pm 0.00033) \times R + (3.04 \pm 0.43).$$

The comparison with relations obtained in [3] emphasizes several important inferences. Magnitude relations for the body wave magnitudes and the surface wave magnitudes differ less between the two studies than the local magnitude and the duration magnitudes. It is probably related to the larger numbers of measurements used in the calculation of the magnitude relations for the body wave magnitudes and the surface wave magnitudes, decreasing statistical fluctuations and leading to stability of the estimates. Uncertainties of the estimates for the body wave and surface wave magnitudes are smaller in this study where more data are used in respect to the data used in [3]. It is an indication that the magnitude relations may approach stability. Both relations for body wave magnitude, M_b and M_b^r, have similar regression coefficients and uncertainties. Thus, it is justified in future studies based on larger data sets to use only one of the relations. Similar behavior is observed also for the surface wave magnitude scales, M_S and M_{S_BB}. Therefore only the M_{S_BB} may be used in future research since there is no necessity to simulate WWWLP records contrary to the *M*s estimates. Uncertainties of the regression coefficients for the duration magnitude relations also diminish in comparison with the previous work [3]. Duration magnitude practically does not depend on the distance, since the corresponding calibration coefficients in both M_d and M_d^r relations are close to zero. Both duration magnitude scales, M_d and M_d^r, have similar regression coefficients and uncertainties; hence it is justified to use only one of them in future studies. The local magnitude depends on distance only by the logarithm term in the regression, while the calibration coefficient for the linear distance term is approximately zero. Regression coefficient A_1 in local magnitude relation is characterized by higher uncertainties than this in [3], while other coefficients have smaller uncertainties. More seismic waveforms measurements are required to reach stability for the local magnitude relation.

We recalculated magnitude estimates for all 758 sets of measurements from individual seismic waveforms by obtained magnitude calibration relations. Next, we estimated different magnitudes (for each magnitude type separately) for each analyzed earthquake as average of relevant station magnitudes. Figs. 3–6 present comparison between magnitude estimates for the analyzed 25 seismic events, calculated on the base of the magnitude relations obtained in this study, relations obtained in [3] and magnitude estimates by relations calibrated for other regions of the globe (for details see [3] and [4]). Relevant reference magnitude values, as given by IDC, are also presented in Figs. 3–6.

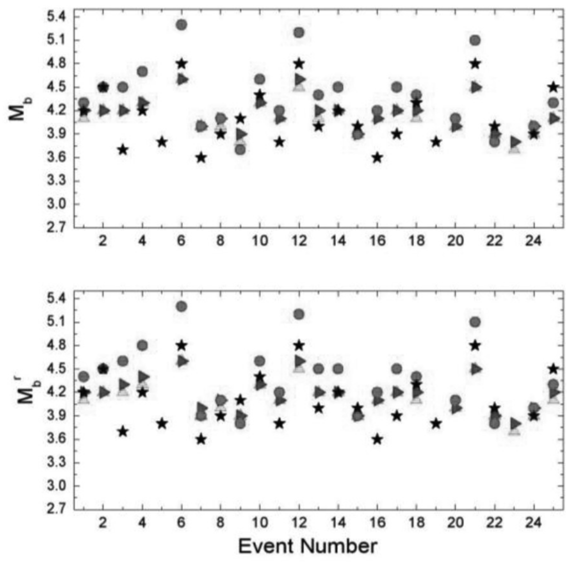

Fig. 3. Comparison between body wave magnitude estimates. Black stars denote reference magnitudes, green triangles – estimates by relations obtained in this study, violet triangles – magnitude estimates by relations obtained in [3], red dots represent estimates based on “global” relations, used for initial magnitude estimates in [3] and [4]

Differences between “local” (Balkan Peninsula specific) and “global” estimates for surface wave magnitudes are smaller than these for other magnitude types. It is an indication that the “global” relation for the surface wave magnitude may be considered relatively appropriate also for Balkan Peninsula’s earthquakes. For the majority of the considered earthquakes single event magnitudes based on the two different relations (in [3] and in this study) coincide completely, except for 3 M_{S_BB} estimates and 5 M_S estimates which differ by 0.1 magnitude units.

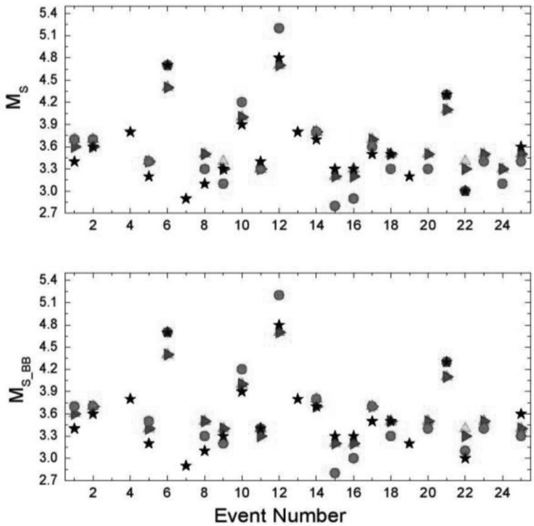

Fig. 4. Comparison between surface wave magnitude estimates. See Fig. 3 for used symbols

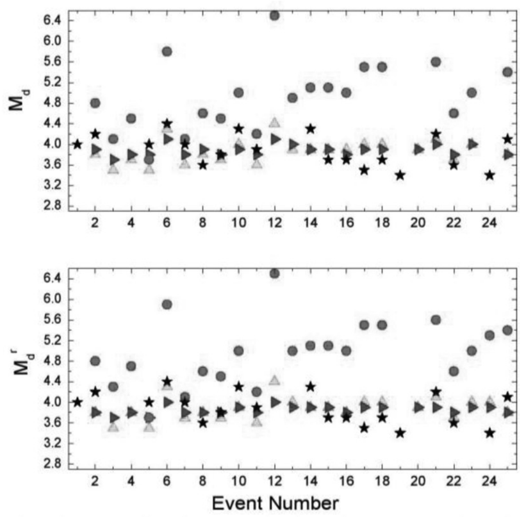

Fig. 5. Comparison between duration magnitude estimates. See Fig. 3 for used symbols

Body wave magnitude estimates in this study and in [3] also differ by no more than 0.1 magnitude units. Differences between "local" and "global" body wave magnitude estimates are relatively low for most of the selected earthquakes, although for a limited number of seismic events the difference is up to 0.6–0.7

magnitude units.

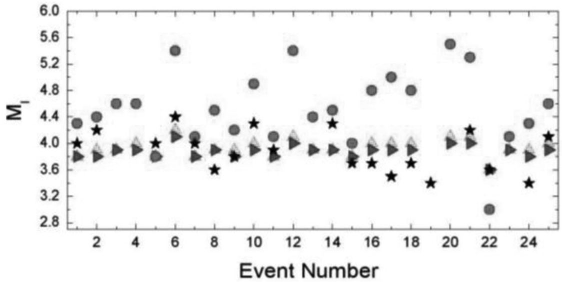

Fig. 6. Comparison between local magnitude estimates. See Fig. 3 for used symbols

Local magnitude estimates in this study and in [3] also differ by no more than 0.1 magnitude units. It is interesting that the difference between these "local" estimates and the "global" M_l magnitude relations may be quite large (up to 1.4 magnitude units), indicating that "global" M_l magnitude calibration is not appropriate for application to Balkan Peninsula earthquakes.

Relatively large are differences (up to 0.3 magnitude units) between the duration magnitude estimates in this study and in [3]. As for the local magnitude estimations, the "global" calibration relation for duration magnitude is not suitable for Balkan Peninsula earthquakes.

4. SUMMARY AND CONCLUSIONS

In this paper we presented new magnitude calibration relations for local magnitude, body wave magnitude (2 scales), surface wave magnitude (2 scales), and duration magnitude (2 scales) derived by VSNSU seismic record measurements. The obtained relations are representative for the earthquakes in the Balkan Peninsula region. Our results improve and precise the magnitude relations obtained in the previous work [3].

Obtained magnitude relations are still preliminary despite the improvements. Many more seismic records should be processed and used in the calibration procedure to obtain more precise and fully operational relations for the Balkan Peninsula region. We plan to process more VSNSU seismogram records including also earthquakes with $M < 4.0$, in order to decrease the uncertainties of the regression coefficients. The obtained Balkan Peninsula magnitude relations may improve the magnitude determination of earthquakes especially in regions near to political borders between the different countries, where magnitude estimates are usually based on seismic stations records from single national network with limited azimuth coverage.

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REFERENCES

[1] ISC International Seismic Center, www.isc.ac.uk, 2017.
[2] IDC International Data Center at CTBTO, www.ctbto.org, 2017.
[3] Raykova, R., M. Tsekov, V. Protopopova, M. Filipova, L. Dimitrova, L. Dimova, In: *Proceedings of the 3rd Bulgarian National Congress on Physical Sciences,* 2016, S0623, 1-10, Heron Press, Sofia.
[4] Filipova, M., R. Raykova. *J. of Physics and Technology,* 2017, **1**, 2 (in press).
[5] EMSC-CSEM, European Mediterranean Seismic Center, www.esmc-csem.org, 2017.
[6] Kaviris G., P. Papadimitrios, and K. Makropoulos. In: *Proceedings 11th International Congress, Athens*, 2007.
[7] Craiu, M., A. Craiu, C. Ionescu, M. Popa, and M. Radulian. *Romanian Reports in Physics*, 2012, **64(4)**, 109.
[8] Hothorn T., B. Everitt. A Handbook of Statistical Analyses Using R. Boca Raton, Florida, 2014.