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Magnitude Determinations from Records of the VSNSU Seismic Stations

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Abstract. Virtual Seismological Network of Sofia University (VSNSU) was launched in 2015 within the framework of a research project, funded by Sofia University. Sixteen seismic stations from several national and international networks in southeastern Europe with open real time data access were selected. Eleven earthquakes, located in southeastern Europe, were analyzed in order to obtain estimates of different magnitude types (M_l, M_S, M_b, M_d) by measuring amplitudes and their periods, as well as the earthquake's duration for each seismic record. First approximations of magnitude formulae specific to VSNSU were obtained by multiple linear regression method using as a reference values estimated by IDC for relevant magnitude scales.

1 Introduction

Virtual Seismic Network of Sofia University “St. Kl. Ohridski” (VSNSU) was established in 2015 within the framework of a research project funded by Sofia University. The network consists of 16 seismic stations located in the Balkan Peninsula region (Figure 1). The stations belong to 6 national networks: one Bulgarian [1], one Romanian [2], one Serbian [3], two Greek [4, 5], one Turkish [6], as well as two international networks: MedNet [7], and Geofon [8]. The seismic records were obtained from IRIS [9] and EIDA [10] data centers. Additional information for the analyzed earthquakes was obtained from webpages of EMSC [11] and ISC [12]. Generally, earthquake's parameters such as epicenter, depth, origin time and magnitudes, reported by individual networks may differ, even significantly [12].

2 Magnitude Calculations

We defined and calculated magnitudes of four different types for stations from VSNSU. Eleven earthquakes in the Balkan Peninsula region (latitudes between 35°N-45°N and longitudes between 20°E-30°E) with magnitude equal to or greater than 4.0 were selected [11]. Locations of the earthquakes are shown in Figure 1 and parameters of each event are listed in Table 1. For each event, one-hour record in SEED data format was obtained and converted to SAC seismic format. The software package SAC [13] was used to apply the station instrument response to the original records in counts and to obtain the Wood-Anderson seismometer simulation records, WWSSN-LP seismometer simulation records, or velocity broad-band records, filtered in different frequency bands. For further analyses, every record was exported and converted into ASCII file, containing time and amplitude. We applied several widely used magnitude relations to calculate M_l, M_S, M_b, and M_d magnitudes from VSNSU records.

Following Richter definition, the local magnitude M_l was obtained by measuring the maximum amplitude A_H in μm (as average value of two horizontal components), as well as determining the hypocentral distance R in km. Additionally, we measured the time difference t_{sp} between first P- and S-wave arrivals (in seconds). Prior to measuring amplitudes, the seismic records were transformed to simulate Wood-Anderson seismometer response, since originally local magnitude was defined for this type of seismometer. To calculate the local magnitude we used the equation [14]:

$$M_l = \log(A) + 1.11 \times \log(R) + 0.00189 \times R - 2.09\,, \qquad (1)$$

Table 1: Parameters of the analyzed events [11].

Event	Date	Time	Lat.(°N)	Lon.(°E)	Depth (km)	Magnitude
$ev02$	2016-01-04	18:00:54	38.58	20.60	10f	M_b 4.6
$ev04$	2016-01-19	19:04:43	36.65	26.94	137f	M_b 4.7
$ev06$	2016-02-15	18:55:00	37.58	21.70	50f	M_b 5.1
$ev08$	2016-02-28	11:17:18	41.47	22.93	20	M_l 4.0
$ev11$	2016-03-12	12:40:39	35.23	23.52	10	M_W 4.6
$ev14$	2016-03-24	01:22:18	36.01	29.62	20	M_W 4.7
$ev15$	2016-03-29	01:05:30	37.44	20.11	10	M_W 5.3
$ev17$	2016-04-01	14:30:48	35.97	25.19	88	M_l 4.5
$ev18$	2016-04-11	18:53:45	38.22	20.30	12	M_b 4.6
$ev20$	2016-04-17	13:54:49	37.85	23.48	14	M_b 4.4
$ev21$	2016-04-18	06:46:14	42.49	26.04	20f	M_l 4.3

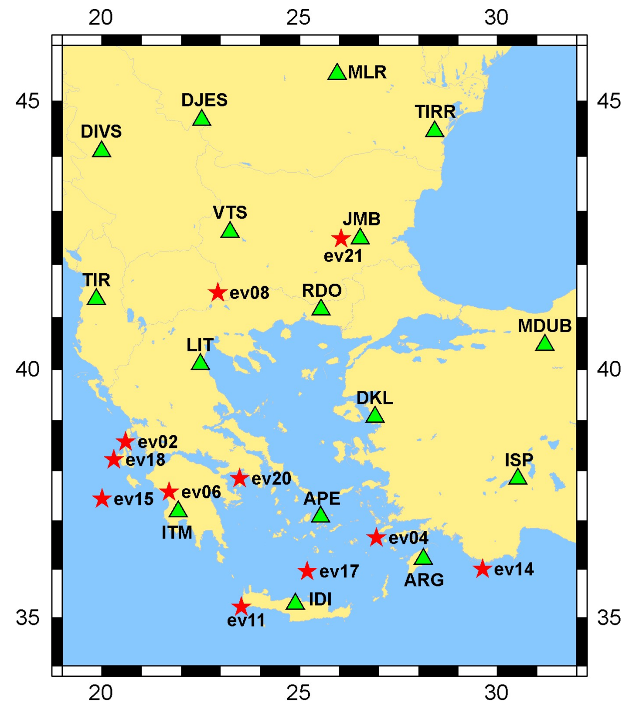

Figure 1: VSNSU seismic stations and locations of the analyzed events.

where the hypocentral distance R is in km. R is calculated as $R = (D_2 + h_2)^{1/2}$ (where D is the epicentral distance in kilometers and h is the hypocenter depth in kilometers) using the location, given by EMSC. Equation (1) was applied for hypocentral distances less than 600 km. Divergence between theoretical and measured travel time difference tsp is used as an indicator of the discrepancy between the utilized velocity model and the real subsurface structure between the earthquake epicenter and the seismic station. Epicentral distances of the selected earthquakes are less than 1500 km thus the equations for body wave magnitude M_b, recommended by IASPEI [14], are not applicable in this study. To calculate body wave magnitude we used the following equation:

$$M_b^* = \log(V) + 2.3 \times \log(D) - 2.0\,, \tag{2}$$

where V is the maximum amplitude in P-wave train of the record in nm/s. This equation was proposed by Navarro end Brockman [15], analyzing some surface explosions in USA and checked for few earthquakes in Europe by Jacob and Willmore [16].

To take into account the depth of earthquakes that can be significant, we obtained additional estimate of body wave magnitude M_b^{*r}, employing similar equation:

$$M_b^{*r} = \log(V) + 2.3 \times \log(R) - 2.0\,, \qquad (3)$$

but using hypocentral distance R instead of epicentral distance D. It is important, since in several cases, the epicentral distance to the nearest recording seismic station is comparable to the earthquake's depth. We applied both of the equations (2) and (3) to the earthquakes with epicentral distances less than 1500 km, i.e. to all analyzed earthquakes. M_b^* and M_b^{*r} estimates differ by less than 0.01 for shallow earthquakes and differ by up to 0.4 for deep events ($h > 50$ km).

The surface wave magnitude M_S was obtained, measuring the maximum amplitude A (in nm) and its period T (in seconds) on the vertical component. We used WWSSN-LP instrument simulation records, filtered between 10 and 30 s, in order to obtain periods close to 20 s. The equation recommended by IASPEI [14] is:

$$M_S = \log(A/T) + 1.66 \times \log(\Delta) + 0.3\,, \qquad (4)$$

where Δ is the epicentral distance in degrees, $\Delta > 2^\circ$, and $h < 60$ km. The epicentral distances of all analyzed earthquakes are less than 1500 km, thus the period of the surface wave with maximum amplitude is around 10 s. We applied also the IASPEI definition [14] for surface wave magnitude, obtained from broad-band velocity records:

$$M_{S\_BB} = \log(V/2\pi) + 1.66 \times \log(\Delta) + 0.3\,, \qquad (5)$$

where V is the amplitude (in nm/s) of the maximal train of surface waves for periods between 3 s and 60 s. This equation can be applied for earthquakes with epicentral distances $\Delta > 2^\circ$.

We applied both formulae (4) and (5) to obtain surface magnitude estimates for the analyzed seismic events. For most of the events, M_S and M_{S_BB} have similar values and differ by less than 0.2. We obtained duration magnitude M_d estimates using the equation proposed in [17]:

$$M_d = 2.00 \times \log(\tau) + 0.0035 \times D - 0.87\,, \qquad (6)$$

where τ is the duration of the earthquake s seismic record (in seconds). It is obtained through determination of the noise level in 50s-time- interval immediately preceding the recorded earthquake. The beginning of an earthquake is defined as the time, when the average amplitude in 1s-time- interval is at least twice the noise level. The end of earthquake is defined as the time, when the average amplitude in 10s-time-interval is equal to or less than the noise level. As for the body wave magnitude,

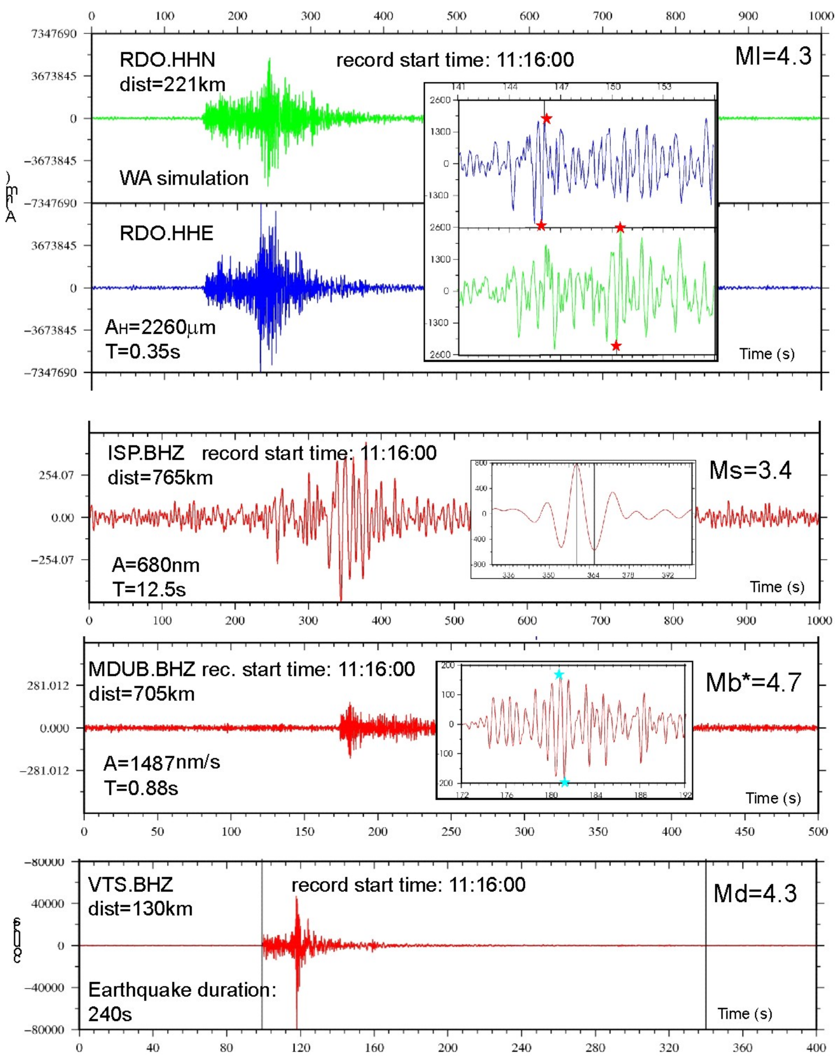

Figure 2: Measured parameters and estimated magnitudes for several stations registering event ev08 (2016-02-28, origin time 11:17:18.0).

we also estimated the duration magnitude using hypocentral distance instead of epicentral distance:

$$M_d^r = 2.00 \times \log(\tau) + 0.0035 \times R - 0.87\,, \tag{7}$$

Duration magnitude was estimated for distances less than 500 km. The difference $M_d^r - M_d$ for the analyzed events is negligible (less than 0.01) for shallow events and have values up to 0.22 for deep earthquakes ($h > 50\,$km).

The measurements of the seismogram parameters (amplitude, period, duration) were done by a script, developed to visualize and to obtain relevant parameters for selected time interval. We used GMT [18] package to plot the seismograms. An example of analysis for event $ev08$ is given in Figure 2. The obtained magnitude estimates for each station, that registered well this event, are shown in Figure 3 as bars with directions equal to epicenter-to-station azimuths and length of bars proportional to the specific magnitude value.

There were a number of problems encountered during the seismic records analysis. Seismic data from stations DKL and JMB were unusable due to non-standard dataless SEED header files an individual procedure should be applied to solve the problem. The stations close to the sea coast exhibited noisy records, that makes difficult the identification and measurement of some earthquake's parameters. It is well known that the radiation pattern of seismic waves varies between 0 and the maximum value, depending not only on the distance and the depth, but also on the azimuth and the focal mechanisms [19]. As a result the values of the magnitude estimates depend also on the set of stations used and can vary significantly.

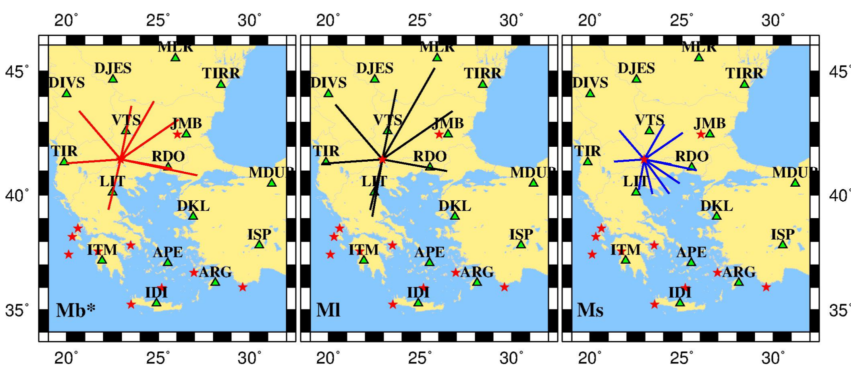

Figure 3: M_b^*, M_l, and M_S estimates for several seismic stations registering event $ev08$.

3 Magnitude calibrations

Magnitude relations (1)–(7) used in the previous section are obtained and calibrated for earthquakes from other regions. Here, we attempted a "local" calibration, i.e. to obtain network specific values of the coefficients A, B, C, and F for each magnitude type, namely:

$$
\begin{aligned}
&M_l = A_1 \times \log(A_H) + B_1 \times \log(R) + C_1 \times R + F_1\\
&M_b^* = A_2 \times \log(V) + B_2 \times \log(D) + C_2\\
&M_b^{*r} = A_3 \times \log(V) + B_3 \times \log(R) + C_3\\
&M_S = A_4 \times \log(A/T) + B_4 \times \log(\Delta) + C_4\\
&M_{S\_BB} = A_5 \times \log(V/2\pi) + B_5 \times \log(\Delta) + C_5\\
&M_d = A_6 \times \log(\tau) + B_6 \times D + C_6\\
&M_d^r = A_7 \times \log(\tau) + B_7 \times R + C_7\,.
\end{aligned}
$$

Multiple linear regression method is routinely used for magnitude scale calibrations, e.g. [20,21]. We applied this method with respect to relevant reference magnitude scales to determine the coefficients A, B, C, and F.

In our study, body wave magnitudes were calibrated with respect to IDC M_b scale, surface wave magnitudes were calibrated with respect to IDC M_S scale, while local and duration magnitudes both were calibrated with respect to IDC M_L scale, i.e. for a specific earthquake we assume that the magnitude used in the regression coincides with the value of the corresponding magnitude (M_b, M_S, or M_L) reported by IDC for this earthquake [12]. Reference magnitude values for each earthquake are listed in Table 2. The numbers of waveforms used in the regression are summarized in Table 3. Applying multiple linear regression method we obtained the following "local" magnitude relations:

$$
\begin{aligned}
M_l = &(0.22 \pm 0.07)\log(A_H)(0.59 \pm 0.80)\log(R) + (0.0018 \pm 0.0011)R\\
&+ (4.03 \pm 1.71) \qquad (8)\\
M_b^* = &(0.52 \pm 0.06)\log(V) + (1.06 \pm 0.14)\log(D)(0.38 \pm 0.51) \qquad (9)\\
M_b^{*r} = &(0.51 \pm 0.06)\log(V) + (1.10 \pm 0.15)\log(R)(0.45 \pm 0.53) \qquad (10)
\end{aligned}
$$

Table 2: Reference magnitudes [12].

	$ev02$	$ev04$	$ev06$	$ev08$	$ev11$	$ev14$	$ev15$	$ev17$	$ev18$	$ev20$	$ev21$
M_L (IDC)	4.2	-	4.4	3.6	4.3	3.9	-	-	4.3	3.7	3.7
M_b (IDC)	4.5	4.2	4.8	3.9	4.4	3.8	4.8	4.0	4.2	4.0	3.6
M_S (IDC)	3.6	3.8	4.7	3.1	3.9	3.4	4.8	3.8	3.7	3.3	3.3

Table 3: 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	55	91	91	93	95	32	33

$$M_S = (0.69 \pm 0.04)\log(A/T) + (0.50 \pm 0.14)\log(\Delta) + (1.84 \pm 0.13) \quad (11)$$

$$M_{S\_BB} = (0.71 \pm 0.04)\log(V/2\pi) + (0.51 \pm 0.14)\log(\Delta) + (1.76 \pm 0.13) \quad (12)$$

$$M_d = (0.82 \pm 0.24)\log(\tau) + (0.00018 \pm 0.0005)D + (1.79 \pm 0.66) \quad (13)$$

$$M_d^r = (0.82 \pm 0.25)\log(\tau) + (0.00017 \pm 0.0005)R + (1.82 \pm 0.67) \quad (14)$$

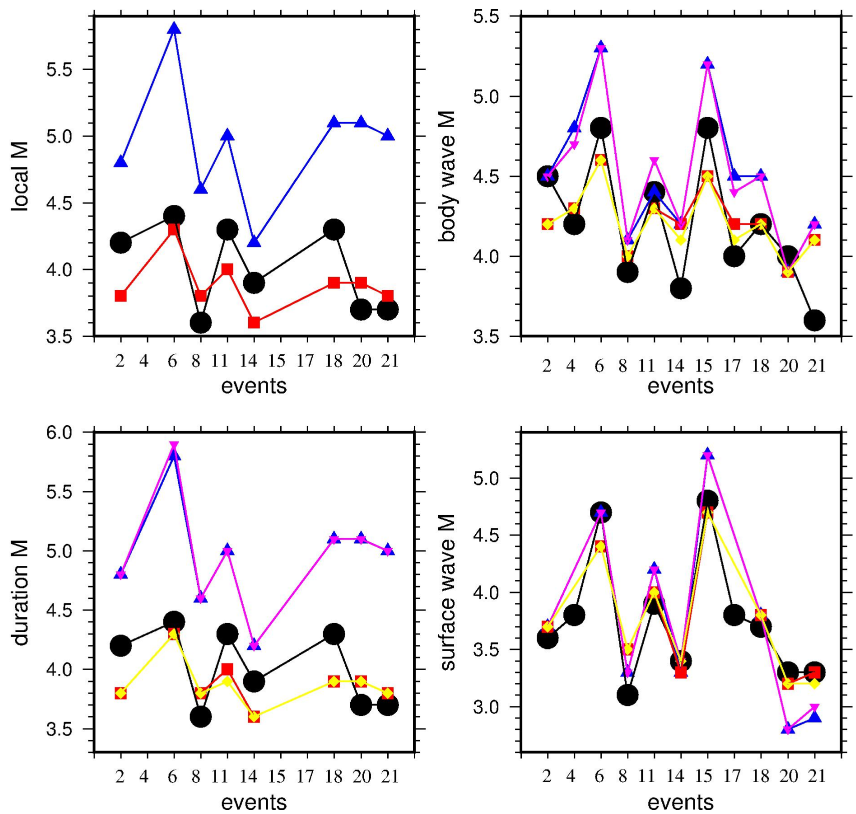

Figure 4: Comparison between different magnitude estimates. Black dots denote relevant reference magnitudes, red squares and yellow diamonds stand for “local” values of relevant magnitudes - equations (8)–(14), blue and pink triangles sign the values derived by relations (1)–(7).

Next, we obtained the magnitude estimates (for each magnitude type separately) for each of the eleven earthquakes by averaging magnitude estimates for all available records of the respective earthquake. Figure 1 shows comparison between magnitude estimates for the eleven analyzed events, obtained by the "local" magnitudes relations (8)–(14), magnitude estimates through relations (1)–(7) used in the previous section ("general" formulae), and reference magnitude values given by IDC. Note that for all magnitude scales, except for the surface wave magnitudes, magnitude estimates obtained by the "general" relations are systematically shifted in respect to the magnitude estimates obtained by the "local" relations. There is no improvement in body wave magnitude determination, when D or R was used. Comparing relations (9) and (10), we found that coefficient B_2 is similar to B_3 with almost the same uncertainty. Relations (13) and (14) for duration magnitude have almost the same coefficients. The differences between M_S and M_{S_BB} are relatively small. Nevertheless, the uncertainties in the coefficients estimates in the "local" magnitude relations are very large. Thus, relations (8) to (14) should be considered as preliminary and not used in the routine processing of magnitudes from VSNSU seismic records. When new measurements will be available, these relations will be regularly upgraded, until the uncertainties become small enough to use them for routine magnitude estimates from VSNSU data.

4 Summary and Conclusions

Several types of earthquake magnitude estimates are routinely processed in the seismic observatories. Here, we presented results from first evaluations of local magnitude, body wave magnitudes, surface wave magnitudes, and duration magnitudes from VSNSU seismic record measurements. We tested procedures for routine seismogram processing to obtain the respective magnitude estimates, and we identified several problems and pitfalls in the procedures. In our magnitude evaluations we used magnitude relations proposed by several authors and calibrated for different regions. Moreover, we applied multiple linear regression method to obtain preliminary specifically calibrated body wave, surface wave, local, and duration magnitude scales. These will be regularly updated and improved with accumulation of new measurements. Our results will contribute to the development of unified magnitude scales for the Balkan Peninsula region.

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References

[1] BS (2016) Bulgarian seismological network, www.geophys.bas.bg.

[2] RO (2016) Romanian seismic network, http://www.fdsn.org/networks/detail/RO/

[3] SJ (2016) Serbian seismological network, http://www.seismo.gov.rs.

[4] HL (2016) National Observatory of Athens Digital Broadband Network, http://dx.doi.org/doi:10.7914/SN/HL

[5] HT (2016) Aristotle University of Thessaloniki Seismological Network, http://dx.doi.org/doi:10.7914/SN/HT

[6] KO (2016) Kandili Observatory Digital Broadband Seismic Network, http://dx.doi.org/doi:10.7914/SN/KO

[7] GE (2016) Geofon, http://dx.doi.org/doi:10.14470/TR560404

[8] MN (2016) Mednet, http://dx.doi.org/10.13127/SD/fBBBtDtd6q

[9] IRIS (2016) Incorporated Research Institution for Seismology, www.iris.edu.

[10] EIDA (2016) European Integrated Data Archive, www.orfeus-eu.org.

[11] EMSC (2016) European-Mediterranean Seismological Center, www.emsc-csem.org

[12] ISC (2016) International Seismic Centre, www.isc.ac.uk.

[13] Goldstein, P., D. Dodge, M. Firpo, Lee Minner (2003) in *The IASPEI International Handbook of Earthquake and Engineering Seismology* , W.H.K. Lee, H. Kanamori, P.C. Jennings, and C. Kisslinger (eds), Academic Press, London.

[14] IASPEI (2013) Summary of magnitude working group recommendations on standard procedures for determining earthquake magnitudes from digital data, http://colossus.iris.washington.edu/docs/papers/download.

[15] Navarro, R., and Brockman, F. R. (1970) Publication USCGS, No. 7465.

[16] Jacob, A. W. B., and Willmore, P. L. (1972) Nature, Lond. **236** 305.

[17] Lee, W. H. K., Bennett R. E., Meagher K.L. (1972) A method of estimating magnitude of local earthquakes from signal duration. USGS report.

[18] Wessel, P., W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe (2013) EOS Trans. AGU **94** 409.

[19] L. Christoskov (2007) *Seismology*, vol. 2, St. Kliment Ohridski Univ. Press, Sofia (in Bulgarian).

[20] Kaviris G., Papadimitrioll P., and Makropoulos, K. (2007) Proceedings 11th International Congress, Athens.

[21] Craiu, M., Craiu, A., Ionescu, C., Popa, M., and Radulian, M. (2012) Romanian Reports in Physics **64(4)** 109.