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DIGITAL BROADBAND SEISMOMETERS OF NOTSSI FOR PRACTICAL MAGNITUDE DETERMINATIONS OF P WAVES

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Abstract. The paper aims to define an appropriate magnitude calibration function and station corrections of PV (PV_S) wave for broadband (BB) instruments of the National Operative Telemetric System for Seismological Information (NOTSSI). The calibration function is defined by an adaptive treatment of the existing calibration function for the short period seismometers. The existing magnitude station corrections are reconsidered in level and the corrections for the new broadband stations are determined. The values of the adapted calibration function and the new set of station corrections have to be considered as a necessary step for realization of practical comparative proof of NOTSSI magnitude determinations regarding the assessments of the international seismological centres as EMSC, NEIC or ISC.

Key words Magnitude, calibration function, station corrections, P wave, broadband seismometer

Introduction

The earthquake magnitude is the most important standard parameter for energy classification of earthquakes and it is a basic tool for solving a lot of important seismological problems, especially for elaboration of homogeneous and compatible earthquake catalogs on local and regional scale. The existence of several magnitude scales used by seismologists all over the world forced the unification of magnitude determinations (Christoskov, 1994, Karnik and Christoskov, 1977, Christoskov et al., 1985, Christoskov, 1991, Bath, 1969, Samardjieva and Christoskov, 1985, Christoskov and Samardjieva, 1988, Ванек et al., 1962, Ванек et al., 1980, Christoskov et al., 1991, Христосков,2005, Христосков, 2007). Unified scales for the Central Balkans were achieved by deriving amplitude/calibration curves for different types of seismic waves (Christoskov, 1994). The calibration functions for shallow events at distances up to 10° were calculated and used for P, S and L waves for short (SP) and medium period (MP) seismographs. The derived calibration functions for MP seismographs are described in Karnik and Christoskov (1977), Christoskov (1985), Christoskov (1991), Bath (1969). The first calibration curves for SP seismographs were obtained for the vertical components of P, S and L waves, denoted as PVs, SVs and LVs (Samardjieva and Christoskov, 1985, Christoskov and Samardjieva, 1988) after the establishment of the National Operative Telemetric System for Seismological Information (NOTSSI).

In the last decades new broadband (BB) seismographs and digital acquisition systems were introduced in the seismological practice. The sensitivity and the frequency response of the new instruments required a certain renewal of the procedures for magnitude determinations regarding the level and shape of the calibration functions and the values of station corrections. The new BB type seismological equipment of NOTSSI (Report, 2005) also imposes an updating of the existing calibration curves and station correction values. The aim of the paper is to define an appropriate calibration function and station corrections of PV (PV_S) wave for BB instruments through re-examination the calibration functions and station corrections for NOTSSI.

Short outlines of NOTSSI regarding the dynamic investigations of seismic waves

NOTSSI becomes operative in 1980 and consists of fifteen periphery seismic stations, equipped with SP vertical seismometers of type S-13 (Teledyne-Geotech) with response characteristics from 10Hz (0.1s) to 1.25s (0.8Hz). The station records are transmitted in real time to the Seismological Centre at the Geophysical institute in Sofia (at present - to the National Data Centre (NDC) of the National Institute of Geophysics, Geodesy and Geography (NIGGG).

In 2005 an overall modernization of NOTSSI instrumentation was performed (Report, 2005). New BB seismometers Guralp 3ESPC, Guralp CMG 40T, KS2000, STS2 and high resolution seismic recorders – model DAS-130-01/3 (Refraction Technology) were installed at all seismic stations. Digital data are transmitted in real-time mode to the NDC at the NIGGG via Virtual Private Network. At the NDC the data are retrieved by the Seismic Network Data Processor (SNDP) software package (Haikin and Kushnir, 2005) for real-time automatic and interactive data processing.

The main seismic station of the NOTSSI is in the observatory Vitosha (VTS) at the locality Zlatni mostove of Vitosha Mountain. Station VTS is most sensitive and low noise station of NOTSSI network (Christoskov et al., 1996, Димитрова, 2009, Christoskov L. at al, 1996). VTS data traditionally are used for precise studies of dynamic characteristic of seismic waves, especially for normalizing (standardization) of magnitude determination, derivation of calibration functions and determination of reliable magnitude corrections. For this type of studies, the wave dynamics comparison between the records of the underground seismometers and those on the earth surface is very important.

The station VTS is equipped with a various type of seismological instruments as SP, MP, BB, very broadband (VBB) instrument and accelerometers. The equipment is installed on concrete pillars in two underground rooms at a depth of 25 m under the surface. The rooms have concrete-brick walls and roofs and are insulated by air joints from the surrounding rock massif (fresh syenite rock). The eighth seismometer pillars are insulated from the concrete room floors and tightly fixed underneath with the rock massif. The seismometer rooms are connected by an underground horizontal 25 m long tunnel with the observatory building. At the basement of the building additionally are located six pillars (Christoskov et al., 1996, Христосков, 2005).

The GURALP seismometers, which vertical component data are mainly used for magnitude determinations, have a dynamic range of more than 120dB and response characteristic from 50Hz (0.02s) to 33s/60s (0.030/0.017Hz) (Fig.1). The standard sensitivity of the seismometers is $2000 V/m/s$ and the channel sensitivity is $1.258\ 10^9 counts/m/s$ (Report, 2005). Equal or very similar to those parameters have the BB seismometers at the all periphery stations of NOTSSI, including the local networks of Provadiya and Kozloduy.

Basic magnitude equations

The earthquakes magnitude remains the most widely used measure of earthquake size and is basic reference parameter in the global and regional earthquake catalogues of the European-Mediterranean seismological center (EMSC), National earthquake information center (NEIC) of USA, International seismological center (ISC), as well as, in the national catalogues and bulletins. At present, there are several magnitude scales applied in seismological practice, but still it is observed an absence of standard methodology and unified magnitude assessments. The widely used magnitude scales by seismological centers are: M_L - local magnitude according the Wood-Anderson formulation (Bath, 1969), m_b - short period (pick response around 1s) body wave magnitude, m_B - wide band/broadband (1-10s) body wave magnitude, M_S - long period (20s) surface wave magnitude, M_W - moment magnitude (Gardini et al., 1997) (see for details Christoskov et al., 1985, Bath, 1969, Samardjieva, and Christoskov, 1985, Ванек et al., 1962, Ванек et al., 1980, Christoskov et al., 1991).

One of the first steps in standardization of magnitude scales at teleseismic distances was achieved by introducing and grounding the following basic formula, later known as the Prague formula (Christoskov et al., 1985, Bath, 1969, Ванек et al., 1962, Ванек et al., 1980):

$$M = \log(A/T)_{\max} + \sigma(\Delta) + S \qquad (1)$$

where M is the magnitude, A/T is the maximum particle velocity of the ground in μ m/s (A is the amplitude and T is the corresponding period), $\sigma(\Delta)$ is the calibration function, S is magnitude station correction. This rather universal magnitude equation is applicable for body and surface waves at wide range of epicentral distances Δ.

According to (1), in case of $n_s>>1$ number of network stations, the magnitude for station i ($i=1,2,...n_s$) and for a given earthquake k ($k=1,2,\dots,n_e$) is determined by the equation

$$M_{ik} = \log(A/T)_{ik} + \sigma(\Delta_{ik}) + S_i \quad (2)$$

and the mean network magnitude M_k for earthquake k ($k=1,2,\ldots,n_e$) is

$$M_k = \frac{1}{n_s}\sum_{i=1}^{i=n_s} M_{ik}\ , \quad (3)$$

where the station correction S_i ($i=1,2,...n_s$) could be determined by the method of the “average magnitude” or the method of the “basic station” (Ванек et al., 1980, Christoskov et al., 1991, Христосков, 2005, Христосков, 2007, Солаков, 1993). The basic station is precisely selected, usually it is the first station of the network ($i=1$) and its station correction is assigned to be zero, i.e. $S_1 \equiv 0$. If the reliable level and shape of σ(Δ) is not known, the procedure for determining correction S_i might be specified as “zero gradient” procedure (Samardjieva and Christoskov, 1985, Christoskov and Samardjieva, 1988). The method of the “basic station” in the version “zero gradient” require comparison log(A/T) values between each station and the basic station at equal epicentral distances to be eliminated the attenuation factor of log(A/T) with Δ. Thus, the correction of station *i* regarding the basic station *1* will be

$$S_i = 1/n \sum_{l=1}^{n} [\log(A/T)_i - \log(A/T)_1]_l\ , \quad (4)$$

i.e. S_i is the mean value of $n>>1$ observations at distances $\Delta_1=\Delta_i$

Applying the above magnitude equations the amplitude curves $A(\Delta)$ and the corresponding calibration functions $\sigma(\Delta)$ for Central Balkans at epicentral distances $\Delta < 10^0$ are defined by the relation (Christoskov, 1994) (for simplicity admitting indices *i* and *k*)

$$A_j(\Delta) = -\sigma_j(\Delta) = \log(A/T)_j + S_j - M \quad (5)$$

where j is the wave type, Δ is the epicentral distance and S_j is the appropriate station correction for a given wave type *j*. This formula was applied for deriving the amplitude-distance curves or calibration functions for different types of seismic waves as $PV, PH, Pg, SH, Sg, LV, LH, PVs, SVs, LVs$ for Central Balkans (Christoskov, 1994).

After the affirmative invasion of the BB digital seismometers in the practice the broadband P-wave magnitude scale (m_B) is defined by a similar to (1) equation

$$m_B = \log(A/T)_{\max} + \sigma_{BB}(\Delta) + S \quad (6)$$

where $(A/T)_{\max} = (V_{\max}/2\pi)$, $V_{\max}$ is the real peak ground velocity in $\mu m/s$ associated with the maximum trace amplitude in the P-phase on vertical-component seismogram, $\sigma_{BB}(\Delta)$ is the calibration function and S is the magnitude correction.

Interdependence of station correction values and the level of calibration functions

From equations (1) and (2) it becomes understandable that the levels (values) of the station corrections and the calibration function are mutually dependent. Preserving the M value unchangeable for a given log(A/T) input, the proportion between station correction values and the calibration function level might be interchanged by a certain constant C≠0. If the correction values are reduced (or increased) by C, simultaneously the calibration function level has to be increased (or reduced) the by C. Therefore, the magnitude M

$$M=\log(A/T)+[\sigma(\Delta)+C] + [S-C]= \log(A/T)+[\sigma(\Delta)-C] + [S+C] \qquad (7)$$

remains unchanged if the proportion between network station correction values and the calibration function level is interchanged by a constant C≠0. This is an important circumstance if the correction value S_1 of the basic station has to be changed in cases like modification of the seismometers' recording conditions, replacement of the basic station by another station of the network, etc.

The above considerations concern the basic station VTS, regarding the seismometers installed in the basement of station building and in the underground pillars at observatory tunnel. The station correction for seismometers on the earth surface was assign to zero, e.i. S=0 (Samardjieva and Christoskov, 1985, Christoskov and Samardjieva, 1988), but for instruments installed in the tunnel it should have a positive value $S_T > 0$ (index T for tunnel). Theoretically, the amplitude on the surface is doubled (2A) due to the sum of incident and reflected wave, but it is reduced to single amplitude (A) at the tunnel (Христосков, 2005, Христосков, 2007). Thus, for magnitude determinations by seismometers in the tunnel, a tunnel correction S_T of about 0.3 (=log2) magnitude units has to be introduced to compensate the amplitude decrease beneath the earth surface. The rate of amplitude reduction depends on the seismometer depth and actually it is less than two times (S_T<0.3). Analogous to VTS is the case with PVL (Pavlikeni) station for seismometers on the earth surface and in the station tunnel. After a detailed study it was found that the station corrections for seismometers in the tunnel are 0.24 for VTS and 0.16 for station PVL (Christoskov, 1994, Христосков, 1991), with a mean value for the tunnel effect about S_T=0.20.

According to Samardjieva and Christoskov (1985) and Christoskov and Samardjieva (1988), the initial contour of magnitude corrections for 10 NOTSSI stations is equalized by the assumption that the correction for basic station VTS is S=0 (with a remainder of 0.14). Later on, the mean and statistically more representative correction S_T=0.20 for tunnel effect has to be used for leveling of the station correction couture. The new station corrections regarding Christoskov, 1994 and Samardjieva and Christoskov (1985) are given in Table 1.

Table 1. PV-wave magnitude station corrections of NOTSSI for SP or BB seismographs

Station	Instruments	Correction	Remarks
VTS	Guralp 3ESPC	+0.20	basic station, tunnel effect
DIM	3 units S-13	-0.12	pillars on surface
JMB	Guralp CMG 40T	-0.08	pillars on surface

KDZ	Guralp 3ESPC	+0.06	pillars on surface
KKB	Guralp CMG 40T	+0.16	pillars on surface
MMB	STS - 2	+0.19	pillars on surface
MPE	RefTek 151/120	-0.11	pillars on surface, need of specifying
PGB	Guralp CMG 40T	-0.16	pillars on surface, need of specifying
PLD	Guralp CMG 40T	+0.08	pillars on surface
PRD	Guralp CMG 40T	-0.14	pillars on surface, need of specifying
PSN	KS 2000	-0.18	pillars on surface
PVL	Guralp 3ESPC	-0.11	pillars on surface
RZN	Guralp CMG 40T	+0.18	pillars on surface
SOF	3units S-13	-0.44	pillars on surface
SZH	Guralp 3ESPC	-0.11	pillars on surface, need of specifying

Adjustment of PV- wave calibration curves for broadband seismometers

The first preliminary calibration curve $\sigma_{VTS}(\Delta)$ for BB seismometers is obtained using amplitude data from basic station VTS for the time period 2008-2010. The calibration function is derived from a relative small amplitude data set of earthquakes with m_b magnitudes between 3 and 6 at epicentral distances $\Delta<10^o$. The magnitudes m_b are collected from catalogues of NEIC and are used as normalizing values in relations (5) and (6). The accomplishment of this derivation of $\sigma_{VTS}(\Delta)$ for BB records is aiming to compare and control the $\sigma_{VTS}(\Delta)$ values with the level, attenuation gradient and shape of the existing calibration functions for P-wave. The implementation of this derivation is possible because the response characteristics of the BB seismometer Guralp 3ESPC completely cover/envelop the response characteristics of the SP seismometer S-13, as well as, the characteristics of previously used SP seismometers SKM-3 or VEGIK and MP seismometers SK-3 or SKD (Христосков, 2005, Христосков, 2007). The amplitude-frequency characteristics of seismometers S-13, SKM-3, VEGIK, SK-3 and SKD are shown in Fig.1. The magnification of seismometer S-13 for period T=1s at station VTS presented in Fig.1 is V=150000. At other stations of NOSTTI the magnification of S-13 had different values but the characteristics were the same as at station VTS. For comparison the amplitude-frequency response of the broadband seismometer Guralp 3ESPC installed at station VTS is given in Fig.1 also. Deploying of modern BB seismometers eliminates the need of installation of several seismometers with different response characteristics at one seismic station. The characteristic of BB seismometer completely covers all frequency intervals of seismological interest and has dynamic range more than 120dB which is high enough to register both small (M<1) and large (M>5) local and regional earthquakes.

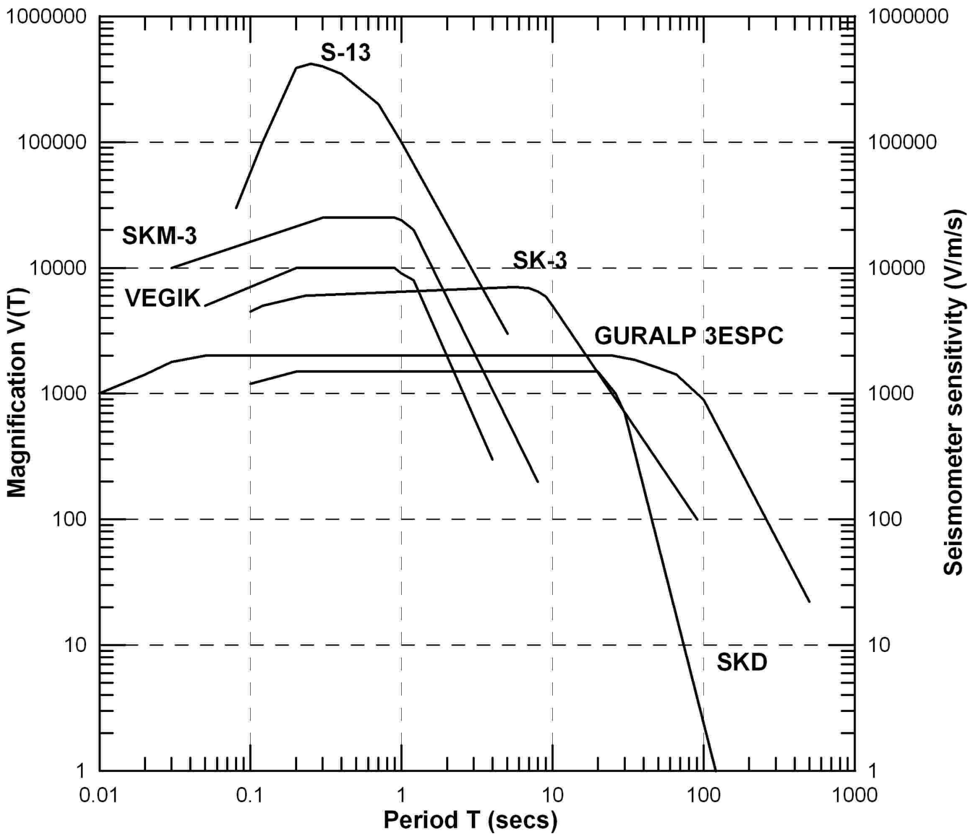

Fig.1. Amplitude-frequency characteristics of seismometers S-13, SKM-3, VEGIK, SK-3, SKD and broadband seismometer Guralp 3ESPC installed at station VTS

To calculate the $\sigma_{VTS}(\Delta)$ calibration function values by equation (5) initially is accepted that the station correction is S_{VTS}=0.20 for BB seismometers in the tunnel. Than, in accordance with equations (5) and (6) is used the relation

$$\sigma_{VTS}(\Delta) = m_b - \log(A/T)_{\max} - 0.20 \qquad (S_{VTS} = S_T = 0.20) \qquad (8)$$

where m_b of NEIC is the normalizing magnitude for m_B determinations of VTS by the amplitude input $(A/T)_{\max}$ of the seismometer Guralp 3ESPC at distances $\Delta < 10^0$. The obtained calibration curve $\sigma_{VTS}(\Delta)$ is shown in fig.3, where it is compared with the calibration function $\sigma_{NOTSSI}(\Delta)$ which traditionally is used for magnitude estimations by SP analog records (Солаков, 1993). The curves are slightly different in shape and level, and they have a similar/common tendency of a slow and smooth increase with the epicentral distance. The possible differences in the shape and level are mainly due to the relative small number (about 50) of $(A/T)_{\max}$ inputs in (8) for deriving statistically reliable values of $\sigma_{VTS}(\Delta)$. It was rather difficult within two years observation period to collect $(A/T)_{\max}$ data for earthquakes in SE Europe and Balkans for which m_b determinations of

NEIC are define and published. Fig.2 shows that the SP calibration curve $\sigma_{NOTSSI}(\Delta)$ from Christoskov and Samardjieva (1988), Солаков (1993) could be accepted as an adequate and reliable version for $\sigma_{BB}(\Delta)$ calibration function, i.e. the relation $\sigma_{BB}(\Delta)$ □ $\sigma_{VTS}(\Delta)$ □ $\sigma_{NOTSSI}(\Delta)$ should be considered as satisfactory representative for practical application. The numerical values of the calibration function of P waves at epicentral distance up to 10^0 are given in Table 2. Additional $(A/T)_{\max}$ data of BB stations of NOTSSI and an extensive data set of m_b determinations from NEIC should be a base for the further finalization of BB calibration function and station corrections for NOTSSI network.

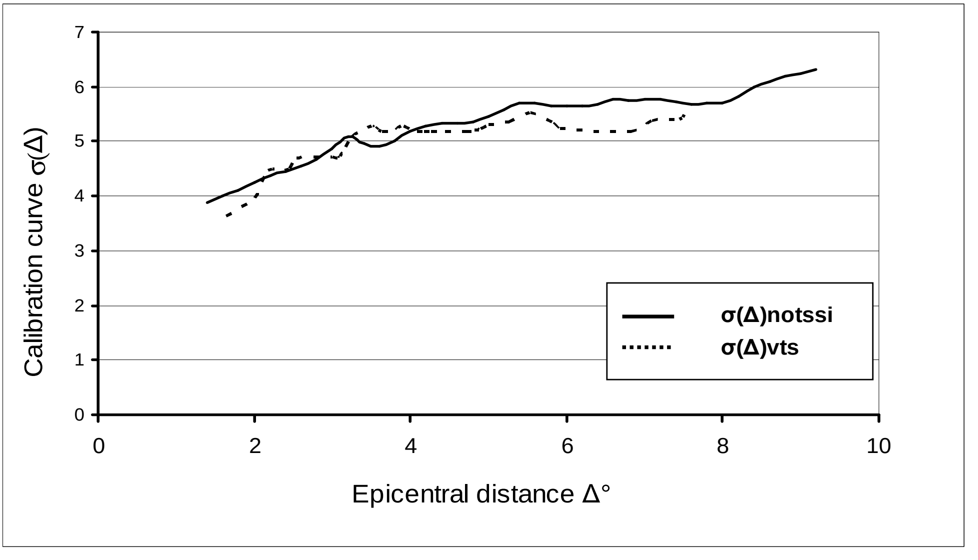

Fig.2. Calibration functions $\sigma_{NOTSSI}(\Delta) = \sigma_{VTS}(\Delta)$

Table 2. Calibration function $\sigma_{BB}(\Delta^o)$ for broadband seismometers of NOTSSI at epicentral distances Δ^o up to 10^o

Δ^o	$\sigma_{BB}(\Delta^o)$	Δ^o	$\sigma_{BB}(\Delta^o)$	Δ^o	$\sigma_{BB}(\Delta^o)$	Δ^o	$\sigma_{BB}(\Delta^o)$
0.0	1.90	2.6	4.31	5.2	5.34	7.8	5.46
0.2	2.26	2.8	4.43	5.4	5.45	8.0	5.46
0.4	2.67	3.0	4.63	5.6	5.46	8.2	5.59
0.6	3.06	3.2	4.84	5.8	5.42	8.4	5.76
0.8	3.19	3.4	4.73	6.0	5.41	8.6	5.86
1.0	3.30	3.6	4.67	6.2	5.41	8.8	5.94
1.2	3.44	3.8	4.76	6.4	5.43	9.0	6.01
1.4	3.63	4.0	4.94	6.6	5.54	9.2	6.07
1.6	3.76	4.2	5.04	6.8	5.50	9.4	6.12

1.8	3.86	4.4	5.09	7.0	5.54	9.6	6.17
2.0	4.01	4.6	5.09	7.2	5.54	9.8	6.21
2.2	4.13	4.8	5.11	7.4	5.49	10.0	6.24
2.4	4.20	5.0	5.22	7.6	5.44		

Network magnitudes m_B of NOTSSI and m_b determinations of NEIC

The earthquakes data for derivation of $\sigma_{VTS}(\Delta)$, supplemented by the available $\log(A/T)_{max}$ data of the NOTSSI stations, are used to perform a preliminary comparative study between m_B magnitudes of NOTSSI and m_b determinations of NEIC. Actually, this comparison is representative also for m_b values of EMSC, as in the used earthquake data set, the magnitude of determinations of NEIC and EMSC do not differ more than ±0.3 magnitude units.

The individual station magnitudes m_B are determined by equation (6) for $\sigma_{BB}(\Delta) = \sigma_{NOTSSI}(\Delta)$ and station corrections from Table 1. The mean m_B magnitudes of NOTSSI are calculated according to equation (3) for $n_S \geq 3$ individual station determinations.

The results of the comparison are illustrated in Fig.3, where m_b and m_B magnitudes for each earthquake (n=34 cases) are plotted together in dependence of the epicentral distance Δ^o to the basic station VTS. This mode of plotting is fruitful by two reasons: firstly, on the ordinate axis directly are seen the differences between each pair m_B and m_b, and secondly, these deviations can be traced out within a wide range of epicentral distances ($1 \geq \Delta^o < 10$). The significance of the magnitude differences $\delta m = m_B - m_b$ along the ordinate axis can be assessed by mean difference $\delta = \Sigma\delta m/n$, standard deviation $\mu = [(\Sigma\delta m^2 - n\delta^2)/(n-1)]^{1/2}$ and the deviation in the mean $\nu = \mu/n^{1/2}$, which are respectively $\delta = -5.9\ 10^{-4}$, $\mu = 0.3$ and $\nu = 0.05$. These statistical valuations are an adequate verification for the applicability of P-wave BB magnitudes of NOTSSI for practical purposes.

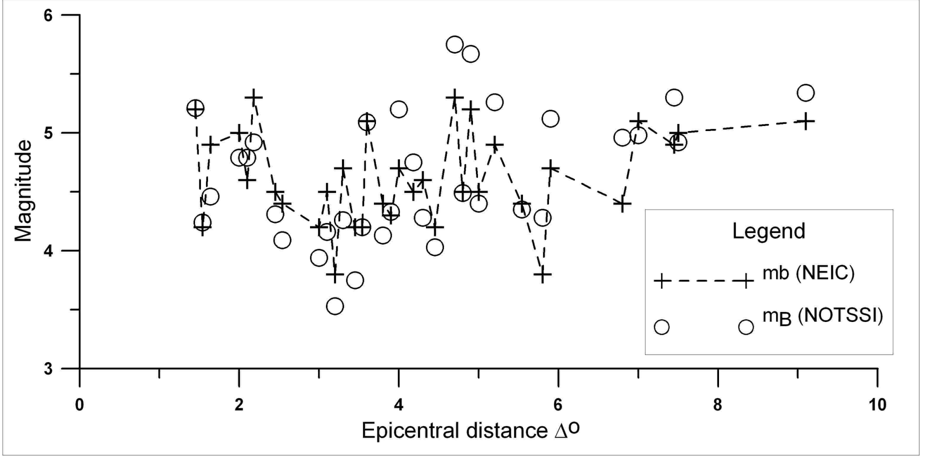

Fig.3. Interrelation between m_B and m_b magnitudes in dependence of the epicentral distance Δ° towards VTS station

The effective practical use of P-wave BB magnitudes means the m_B values to be announced in operative order, for the rapid (automatic) epicenter determinations by NOTSSI network, i.e. within several minutes after the earthquake occurrence. The accuracy of the epicentral coordinate determination, for magnitude assessment – the epicentral distances, depends on geometry/aperture of the NOTSSI stations and the actual epicenter position. For local and near events with epicenters within/around the stations geometry contour the accuracy is satisfactory and the epicentral distances are accurate enough for m_B determinations. For rather distant events ($\Delta > 6^o$) the rapid determinations of the epicentral distances are needed of certain specifications using data from the neighbor countries/networks, consequently, the m_B magnitudes have to be verified and reassessed if necessary.

Conclusion

The magnitude calibration function and the station corrections of P wave (vertical component PV) for broadband seismometers of NOTSSI are defined for practical use. The results show that the calibration function for BB instruments does not differ from the existing calibration function for the short period seismometers. The magnitude station corrections are reconsidered in level and corrections for the new BB stations are evaluated. The newly evaluated calibration function and station corrections allow not only a more reliable determination of the body-wave magnitude m_B but also allow for further precise comparative studies for magnitude unification between the regional networks as NOTSSI and the international seismological centres like EMSC and NEIC.

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Практическо определяне на магнитуда по Р вълни чрез цифровите широколентови сеизмометри, използвани в НОТССИ

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Резюме. Целта на настоящата статия е да дефинира подходяща калибровачна функция и станционни поправки по Р вълни (вертикална компонента PV) за широколентовите сеизмометри, с които е оборудвана Националната оперативна телеметрична система за сеизмологична информация (НОТССИ). Калибровачната функция е дефинирана чрез араптиране на съществуващата калибровачна функция за късопериодни сеизмометри. Магнитудните станционни корекции за новите широколентовите сеизмични станции са получени чрез преоценяване на нивата на съществуващите станционни поправки. Прилагането на адаптираната калибровачна функция и новите станционни корекции в практиката на НОТССИ ще доведе до по-точно определяне на магнитуда на земетресенията по обемни вълни и унифициране на магнитудните оценки между регионални мрежи от типа на НОТССИ и международните центрове такива, като EMSC и NEIC.