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THE GEOMAGNETIC STORM ON NOVEMBER 3-4, 2021: SPECTRAL CHARACTERISTICS IN ULF RANGE AT MID LATITUDES

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Abstract. The geomagnetic storm class G3 was recorded on November 3–4, 2021 on the ground-based magnetometers. Using time series of the data corresponding to the horizontal geomagnetic component, the spectral characteristics in the ULF range for the data collected at Panagjurishte (Bulgaria) and Conrad (Austria) observatories are obtained. To obtain the degree of correlation between the X and the Y components at both stations the coherence analysis is used. It was found that the X components have a very high degree of correlation for the entire studied period in the frequency range 0.03125–16 mHz and are fully synchronous in phase. The Y components have significant differences in phase and values of coherence for different frequency ranges. The dynamic spectra depict similar behavior along the X and Y components during the storm. The geomagnetic variations at both observatories were affected at different time scales. The main difference is that the spectral characteristics appear on time scales 200–400s, where disturbances appear simultaneously along the X component at Panagjurishte and along the Y component at Conrad.

Key words: ULF geomagnetic variations, storm, spectral analysis, coherence.

Introduction

The geomagnetic storm is a disturbance of the Earth's magnetosphere caused mostly by solar wind (fully ionized plasma) blow shock and rarely by direct links between the Sun's magnetic field and the Earth's magnetic field. The Earth's magnetic field is measured by satellite and ground-based equipment. These natural phenomena are widely studied during the last few decades (Lakhina and Tsurutani, 2016). Their spectral characteristics, the impact on the ionosphere (Blagoveshchensky and Sergeeva, 2018; Dahal et al., 2022), the electromagnetic pulsations during the storms (Chamati, M., 2018; Marin et al., 2014) as well as a solar wind properties (Borovsky, 2020) are of particular interest. The large-scale spatial structure of the solar wind are studied (J. Borovsky and Denton, 2006; J. E. Borovsky and Denton, 2006). Alteration (lasting a few seconds) in the direction of the interplanetary magnetic field and accompanied by sudden changes in the velocity vector of the solar-wind plasma are also investigated (Gosling et al., 2011, 2009; McComas et al., 1998). Statistical analysis of the latitudinal distributions of the horizontal geomagnetic variations for period of three years are performed (Watermann and Gleisner, 2009).

Data set

A tri-axial induction magnetometer operates at the Geomagnetic Observatory Panagjurishte (PAG), Bulgaria (42.51N/24.18E) as part of the acquisition system that records original data sets for the ULF geomagnetic field variations associated with X (north-south), Y (east-west), and Z (down/vertical) directions. They are sampled at 100 Hz and organized into data files with a duration of one hour. With the aid of software packages, it performs timely verifications of the data files and converts them into data files, sampled at 1 Hz.

The flux-gate magnetometer that operates at Conrad Observatory (WIC), Austria, is a part of the International Real-time Magnetic Observatory Network (INTERMAGNET). Its coordinates are 47.93N/15.86E. The provided data are sampled at 1s along the three directions (X, Y, and Z).

The data set for the values of the local *K* index (Metodiev, M. and Trifonova, P., 2021) was downloaded from: http://www.niggg.bas.bg/observatories-bg/geomagnetic-observatory-pag/%D0%BB%D0%BE%D0%BA%D0%B0%D0%BB%D0%BD%D0%B8-%D0%BA-%D0%B8%D0%BD%D0%B4%D0%B5%D0%BA%D1%81%D0%B8/

The data set for the values of the global K index was taken from: https://www.spaceweatherlive.com/en/archive/2021/11/03/kp.html

Methods

The spectral analysis is performed on the basis of the Wavelet Morlet analysis. Wavelet coherence is used as a measure of the correlation between two time series that contain data for geomagnetic field variations and is based on Matlab software.

Results and discussion

On November 3–4, 2021, the geomagnetic storm class G3 due to the coronal mass ejection (CME) on the sun arrived on Earth around 19:30 UTC. The value of the solar wind speed increased from 500 km/s to 750 km/s, according to OMNIWeb (https://omniweb.gsfc.nasa.gov/form/dx1.html). On Figure 1, the records of the geomagnetic field variations along the X and Y directions from different types of magnetometers located at mid-latitudes—Panagjurishte, Bulgaria, and Conrad Observatory, Austria—are presented.

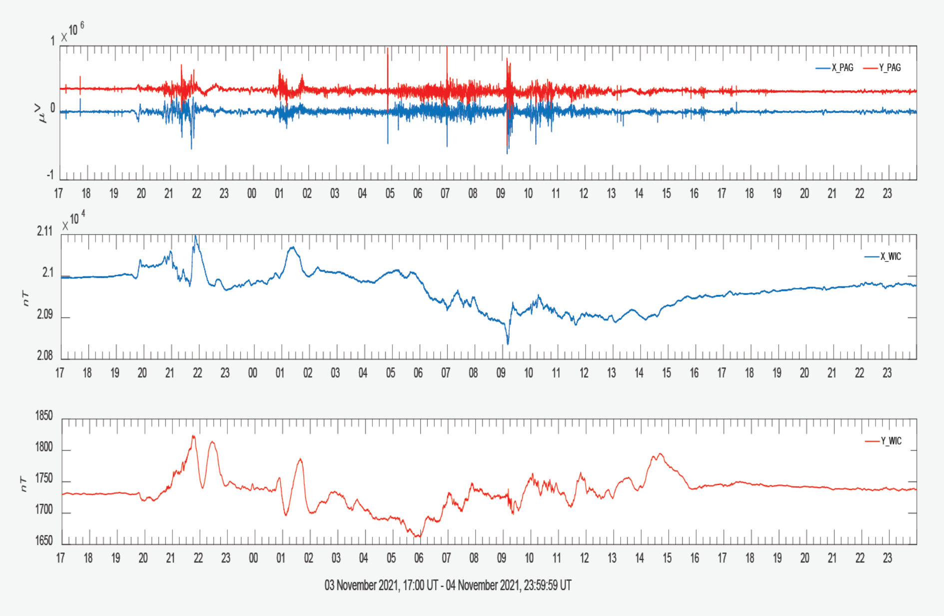

Figure 1. Geomagnetic variations along the X and the Y components on November 3-4, 2021, PAG (Bulgaria) and WIC (Austria) stations.

Figure 2 shows the values of the global *Kp* index on the top panel (https://www.spaceweatherlive.com/en/archive/2021/11/04/kp.html) and the local *K* index values on the bottom panel (Metodiev, M. and Trifonova, P., 2021) calculated for the Geomagnetic Observatory Panagjurishte on November 3–4, 2021.

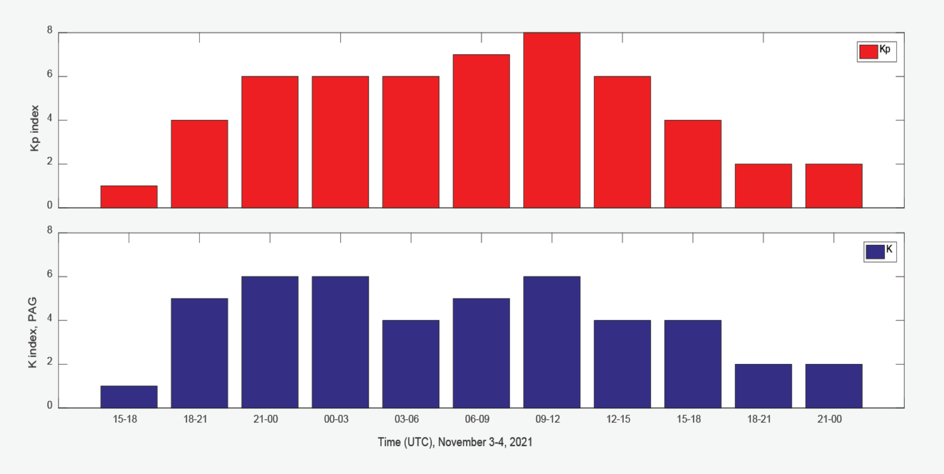

Figure 2. *Kp* and *K* index (PAG), November 3-4, 2021

The Kp index reached 8 - an extremely high value on November 4, 2021 in the time interval 09-12 UTC. During the same time, the K index at Panagjurishte was 6. The local K index values at WIC station are not available, but according to the interactive geomagnetic activity map provided by the INTERMAGNET web site, the local geomagnetic index in the vicinity of Austria stations is very close to that calculated at PAG station.

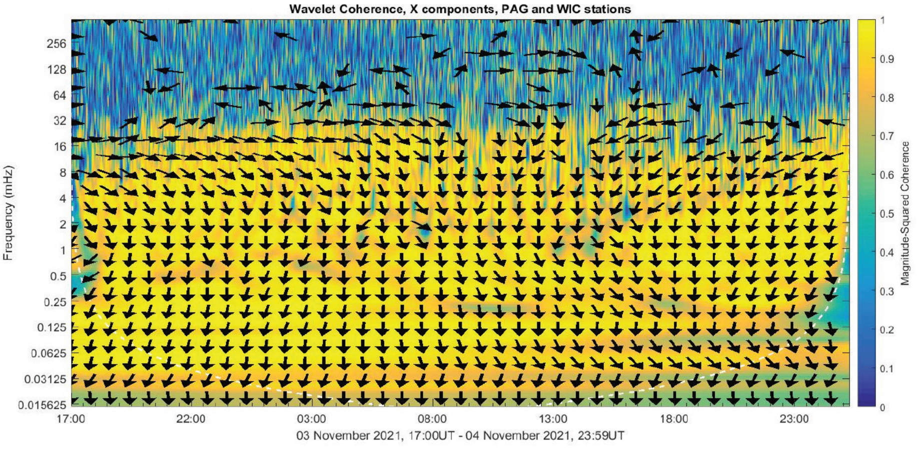

Figure 3. Wavelet coherence, X components (PAG and WIC stations), November 3-4, 2021

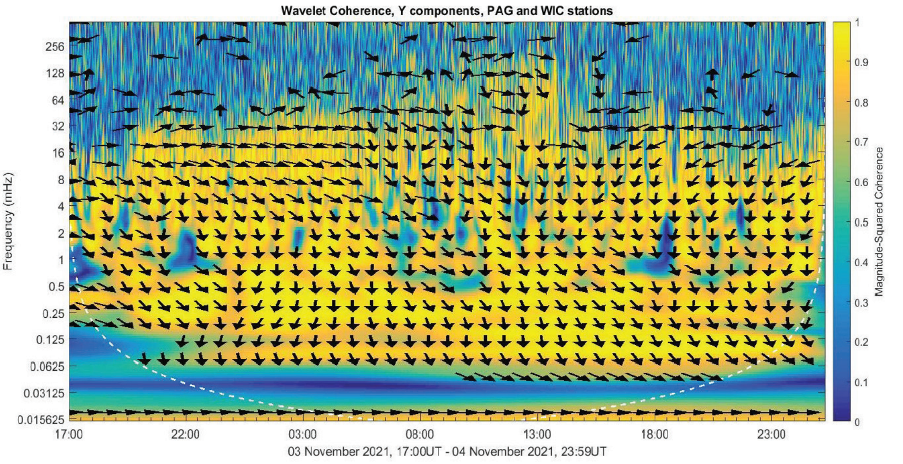

Figure 4. Wavelet coherence, Y components (PAG and WIC stations), November 3-4, 2021

On Figures 3 and 4, the wavelet coherence is obtained as a measure of the correlation between the X components of the two stations (PAG and WIC) along with the Y components. As it is clearly visible, the X components of the two geomagnetic stations have coherence values in the frequency range 0.03125–16 mHz that vary between 0.8 and 1. With black arrows, the direction of the phases is presented. It is fully synced without offset at most frequency ranges. For the Y components (Figure 4), the coherence values differ from those of the X components and remain the same with frequency ranges of 0.25–0.5 mHz and 4–16 mHz, but the phases during the analyzed days are not synced at high frequency ranges. This means that the intensity of the disturbance is, as usual, greater in the north-south direction.

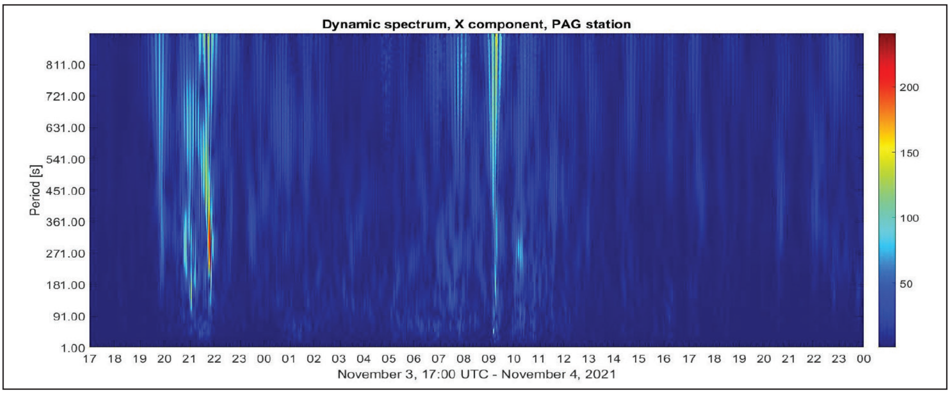

Figure 5. Dynamic spectrum, X component, PAG station, November 3-4, 2021

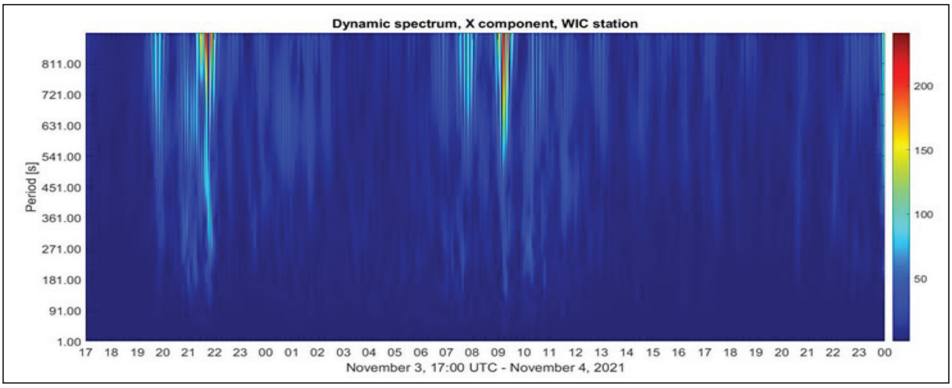

Figure 6. Dynamic spectrum, X component, WIC station, November 3-4, 2021

Figures 5 and 6 depict the dynamic spectra for the X components for the two stations—PAG and WIC. Their spectra are calculated for time scales of 1-900s or frequency ranges of 1 mHz-1 Hz, which correspond to ULF geomagnetic pulsation periods. Time series from the PAG and WIC stations are detrended from linear trends and then analyzed. On the two figures simultaneously, it is visible that the solar wind reached the Earth at about 19:30 UTC on November 3, 2021, when the largest in intensity disturbance is observed. For the PAG station they cover all investigated periods/frequencies, but for the WIC station disturbances appears in the period range 180-900s. The time of appearance is the same for both stations, and they are simultaneous with changes in the K and Kp indexes. At Panagjurishte Observatory at about 22:00 UTC powerful disturbances with periods varying in 200-400s (Pc5 range) are recorded. The differences are probably due to the use of different types of measuring instruments or weaker penetration of disturbance from the north direction.

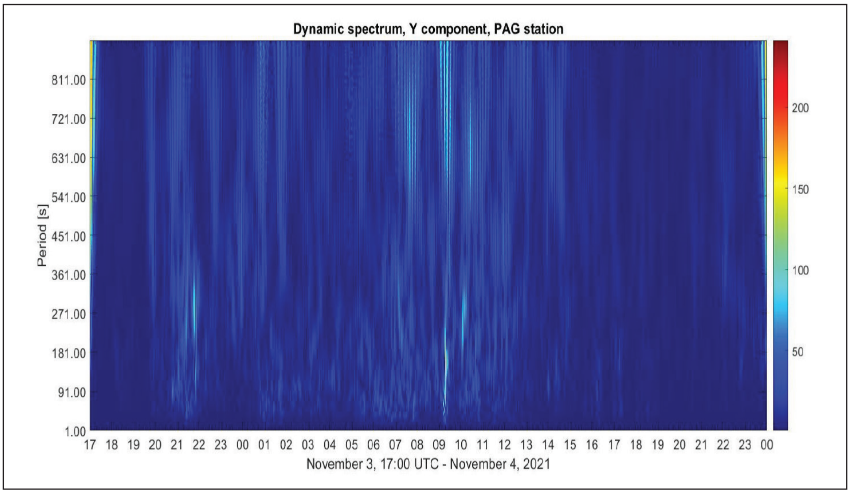

Figure 7. Dynamic spectrum, Y component, PAG station, November 3-4, 2021

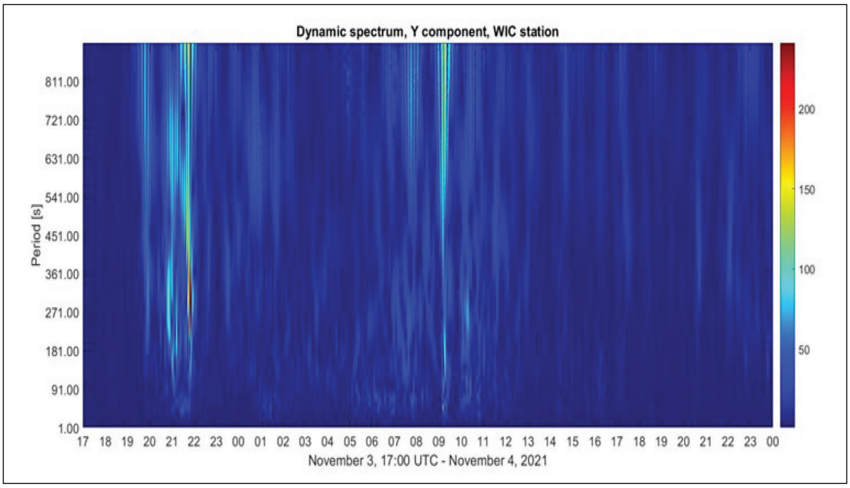

Figure 8. Dynamic spectrum, Y component, WIC station, November 3-4, 2021

Figures 7 and 8 present the dynamic spectra obtained for the Y components for the analyzed geomagnetic stations.

While, both stations show some similarities, they displayed discrepancies as well. The disturbances recorded at WIC (Figure 8) are stronger than at PAG (Figure 7). At time scales 200–400 (Pc5 range), disturbances similar to those observed at PAG station along the X component, also appear along the Y component at WIC station at the same time.

That may be due to the fact that at geographic latitude 47.93N, the penetration of the disturbance along the direction east-west is more pronounced than at latitude 42.51N.

Conclusions

On November 3–4, 2021, the geomagnetic storm class G3 disturbed the Earth's magnetosphere and was recorded from the magnetometers located at the ground-based observatories. The series of data for the geomagnetic field variations along the X and the Y directions recorded in PAG and WIC observatories are analyzed. Wavelet coherence analysis shows full synchronization in the phases and values of coherence in the frequency range 0.03125–16 mHz between the X directions of the two stations and differences along the Y components that are expressed in phase offset and partial synchronization across frequency ranges and time of appearing. The obtained dynamic spectra for the X and Y components show simultaneous disturbances in time scales ranging from 1-900s, which correspond to K and Kp index values. The main difference between the spectra of the stations is that the powerful disturbance in time scale 200-400s (Pc5 range) is observed in PAG station along X direction, but not in WIC station along X direction. This can be seen at WIC station along the Y axis. These discrepancies for the different components of the two stations may be due both to the use of different types of instruments which measure geomagnetic field variations and also to the different penetration of the disturbance at different latitudes.

Acknowledgments. This work is supported by Contract No D01-404/18.12.2020 (Project "National Geoinformation Center (NGIC)" financed by the National Roadmap for Scientific Infrastructure 2017-2023. The results presented in this paper rely on data collected at magnetic observatories. We thank the national institutes that support them and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org).

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Геомагнитната буря от 3-4 ноември 2021: спектрални характеристики в ултра-нискочестотен диапазон, получени за средни географски ширини.

М. Шамати

Резюме. Геомагнитната буря от клас G3 е регистрирана на 3-4 ноември 2021 г. от наземни магнитометри. Използвайки времеви редове от данни за хоризонталните геомагнитни компоненти, са получени спектралните характеристики в ULF диапазона за обсерваториите Панагюрище, България, и Конрад, Австрия. За получаване на степента на корелация между X компонентите и Y компонентите на двете станции, е приложен кохерентен анализ на базата на уейвлет трансформация. От него се установява, че X компонентите на двете станции имат много висока степен на корелация за целия изследван период в честотния диапазон 0.03125–16 mHz и са напълно синхронни по фази. Y компонентите имат значителни разлики във фазата и стойностите на кохерентност за различните честотни диапазони. Динамичните спектри изобразяват подобно поведение по X и Y компонентите по време на бурята. Геомагнитните вариации, записани в двете обсерватории, са засегнати в различни времеви скали. Наблюдава се едновременна поява на смущение по X компонента в Панагюрище и по Y компонента в Конрад обсерваторията във времевите скали 200–400 секунди.

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INVESTIGATION OF THE ULF GEOMAGNETIC NOISE RECORDED ON MAY 1, 2020 AT PANAGJURISHTE GEOMAGNETIC OBSERVATORY

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Abstract. On May 1st, 2020, at the Geomagnetic Observatory in Panagjurishte, Bulgaria, the unusual ultra-low frequency (ULF) geomagnetic noise was recorded by a tri-axial (X, Y, and Z directions) induction magnetometer. The time series from April 1, 2020 till May 1, 2020 are examined. Applying the detrended fluctuation analysis (DFA), the DFA exponent is calculated for the time series along the three geomagnetic directions, and the results show an unusual decrease in values of the DFA exponent in time scales 10-180s and 10-900s that starts after April 29, 2020. Through Magnitude-Squared Coherence analysis, the correlation and phases between every two geomagnetic components are obtained for the time series on May 1, 2020, under very low geomagnetic activity levels. The high values of the coherence and phase full sync for the X and Z components are observed, in the time period 04:00–20:00 UTC, at a frequency range 0.125-0.25 mHz. The present study does not rule out that the considered disturbances have a lithospheric origin.

Key words: ULF geomagnetic variations, DFA analysis, Magnitude-Squared Coherence, Panagjurishte.

Introduction

ULF variations of the geomagnetic field are an integral part of studying the interrelationships in the magnetosphere, ionosphere, atmosphere, and lithosphere systems.

The National Geoinformation Center (NIGGG, BAS) (Miloshev et al., 2019) collects various types of geo-information data, which are linked with many natural phenomena for example the geomagnetic storms, sub-storms and ULF pulsations (Blagoveshchensky and Sergeeva, 2018; Borovsky, 2020; Chamati, 2020; Chamati and Andonov, 2021; Nose et al., 1998), lithospheric geodynamic processes (Aleksandrova et al., 2021;

Oynakov et al., 2021a, 2021b; Popova et al., 2021; Trifonova et al., 2021), geomagnetic field elements (Metodiev and Trifonova, 2020) the air quality, the climate and etc.

The interactions between the lithosphere and the magnetosphere systems are poorly investigated despite the numerous scientific studies in the field. An unsolved problem is whether there is a direct or indirect relationship between earthquakes and the disturbances/variations in the Earth's magnetic field. The main task here lies in separating the different types of disturbances based on their origin. In order to be able to give at least a partial answer to the question of the previously mentioned connections, a good knowledge of the subject area and systematic studies of different types of geo-parameters are required.

For example, many authors have conducted research on this topic, linking it with hard-to-explain peculiar geomagnetic field disturbances (Alperovich et al., 2003; Anagnostopoulos, 2021; Fraser-Smith, 2009; Gotoh et al., 2003; Nenovski et al., 2013), total electron content (TEC) in the ionosphere (Akhoondzadeh, 2012; Zhao and Hao, 2015), ground water level (He and Singh, 2019) and many other parameters.

Data set

A tri-axial induction magnetometer operates in the Geomagnetic Observatory Panagjurishte, Bulgaria (42.51N/24.18E) as part of an acquisition system that records original data sets for the ULF geomagnetic field variations associated with X (north-south), Y (east-west), and Z (down/vertical) directions. They are sampled at 100 Hz and organized in files with a duration of one hour. With the aid of software packages, it performs verifications on the data files and converts them into data files, sampled at 1 Hz.

The data sets for the values of the local *K* index (Metodiev, M. and Trifonova, P., 2021) were downloaded from: http://www.niggg.bas.bg/observatories-bg/geomagnetic-observatory-pag/%D0%BB%D0%BE%D0%BA%D0%B0%D0%BB%D0%BD%D0%B8-%D0%BA-%D0%B8%D0%BD%D0%B4%D0%B5%D0%BA%D1%81%D0%B8/

Methods

The detrended fluctuation analysis (DFA) (Peng et al., 1995) over the time series of geomagnetic field variations is applied. This method is very helpful for determining long-range correlations in time series over various time scales. Moreover, Wavelet coherence is used as a measure of correlation between two time series that contain data for geomagnetic field variations and is based on Matlab software.

Results and discussion

On May 1, 2020, the Geomagnetic Observatory in Panagjurishte recorded an unusual "noise" in ULF variations of the geomagnetic field (Figure 1). They are mainly manifested along the vertical direction, which starts at about 03 UTC and lasts almost until the end of the day.

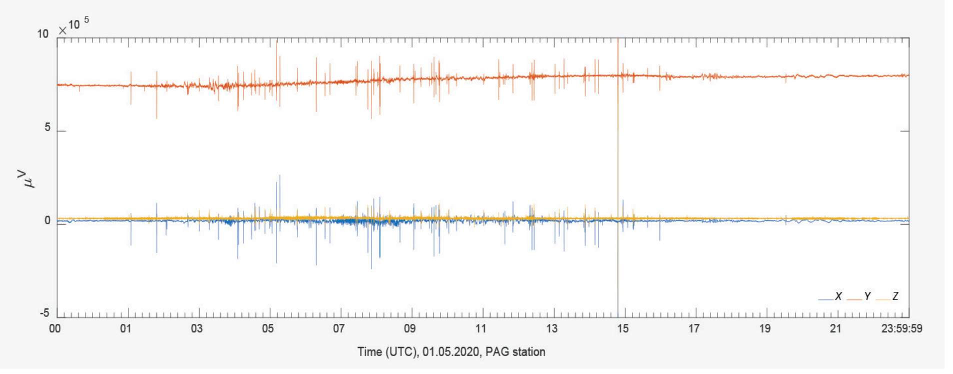

Figure 1. ULF variations along the X, the Y and the Z components on May 1, 2020.

Figure 2 shows the values of the local *K* index (Metodiev, M. and Trifonova, P., 2021) calculated for the Geomagnetic Observatory Panagjurishte on May 1, 2020. The values vary between 0 and 2, which indicate a very low level of geomagnetic activity. The values of the planetary K index have the same values.

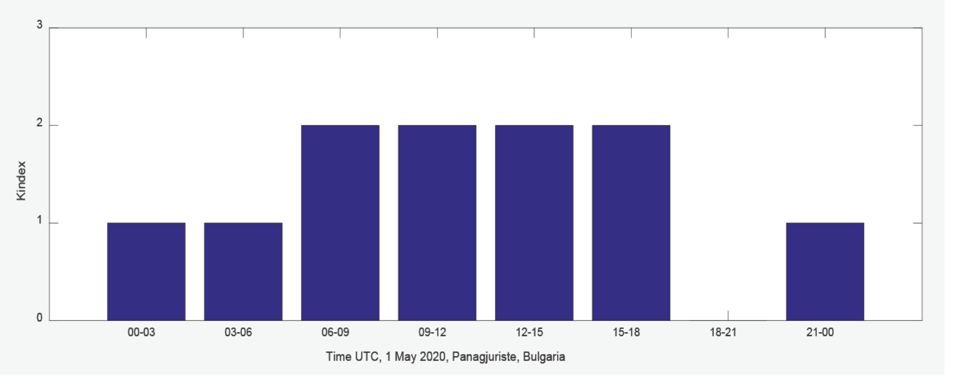

Figure 2. *K* index, May 1, 2020, Panagjurishte, Bulgaria

Next, the DFA is applied to a time series with recorded data along the three main directions (X, Y, and Z) of the ULF geomagnetic field variations. The analysis is performed for the time period April 1, 2020, to May 1, 2020. For each geomagnetic component, for the time scales 10-180s and 10-900s, the DFA exponent is calculated. The results are presented in Figure 3. On the first panel, the DFA exponent calculated for the Z component is shown. Comparison with values of DFA index for the X and the Y components pointed to a decrease of values of DFA exponent (Z component) after April 29, 2020. This decrease of the values indicates that correlations in time series weakened and its self-affinity is changed. The reasons for this decrease in DFA can be due to perturbations with sources in the Earth's magnetosphere, ionosphere, lithosphere, or anthropogenic. The fact that they are predominantly observed in the vertical component of the magnetic field, these variations strengthens the hypothesis that the sources are most likely of either lithospheric, anthropogenic, or mixed origin. To shed some light on the issue of "noise" observed of the vertical component in the time series of data for May 1, 2020, the magnitude-squared coherence, as a measure of correlation between two signals based on wavelet analysis, was obtained.

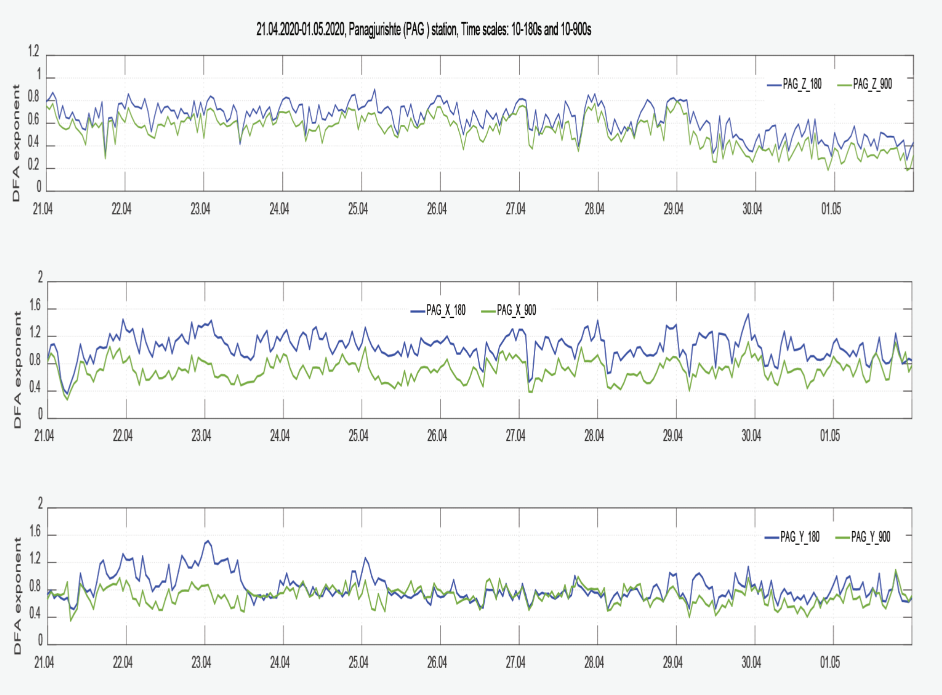

Figure 3. The DFA exponent calculated in time scales 10-180s and 10-900s for the Z, X and Y components, Panagjurishte, 21.04.2020-01.05.2020

Figure 4 shows the changes in magnitude-scored coherence between X and Z directions for May 1, 2020. The coherence has values ranging from 0 to 1 and covers wide ranges of frequencies from 0.015625 mHz to 512 mHz. Figures 5 and 6 show the coherence for the (X, Y) and (Y, Z) components for the same frequency band. With black arrows, the phases are marked. Figure 4 depicts four interesting facts, which is not observed on Figures 5 and 6. Indeed,

1 - High coherence values close to 0.9 in the time interval 04-20 UTC. This one time interval can be divided into three subintervals: 04–11 UTC, 11–15 UTC, and 15-20 UTC.

2 - The coherence's first subinterval has values around 0.9 and covers the frequency range 0.125-0.25 mHz. The black arrows show that the phases of the geomagnetic "noise" along the X and Y directions are different.

3 - full synchronization in phases is observed in the second subinterval after about 11 UTC, but only at 0.125 mHz. For the frequency interval of 0.25–0.5 mHz, the coherence is close to 0.

4 - The phases of geomagnetic "noise" along the X and Z components reach full synchronization at 0.125-0.25 mHz in the third subinterval (after 15 UTC).

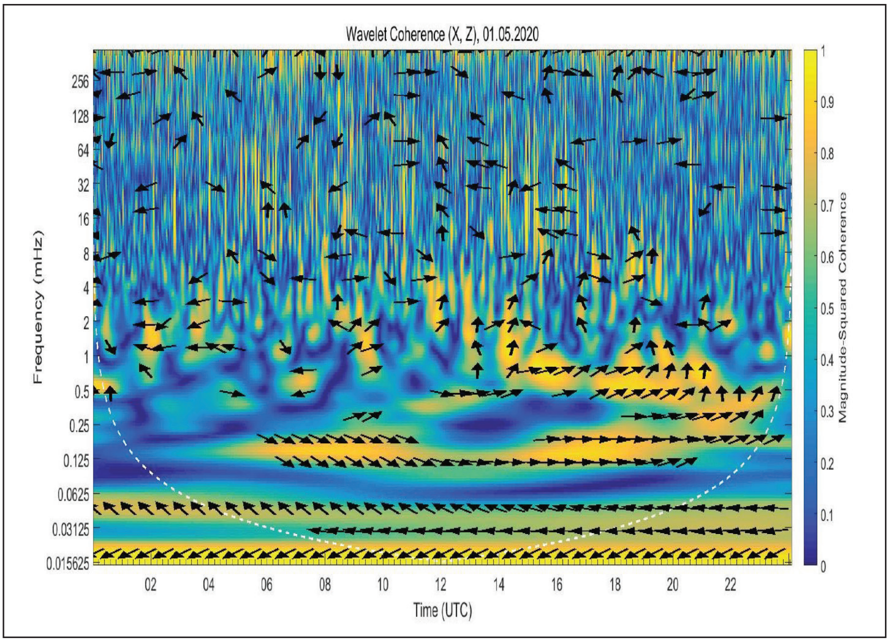

Figure 4. May1, 2020, PAG station, X and Z components

The reasons of this unusual geomagnetic noise, recorded along the vertical (Z) component might have different sources. Here, any simultaneous disturbances, recorded along the three geomagnetic directions at frequency interval 0.125-0.25 mHz, are not observed and this makes the possibility that they have a magnetospheric origin unlikely. From the lithospheric point of view, the one earthquake was recorded at this day. It occurred at 11:01:39 UTC on May 1, 2020 and has a magnitude of Mw=4.6, a depth of 18 km, and an intensity of Io/Imax=5.5. The epicenter has geographic coordinates 42.23N/24.87E, and its distance from Panagjurishte Geomagnetic Observatory is about 65 km in east-south-east direction. The unusual perturbations observed in the vertical component coincide well with the time the earthquake occurred. The facts that have been discussed cannot rule out the possibility that the cause of the disturbances on the Z component could be the preparation of the earthquake or that the observed effects are a co-seismic effect.

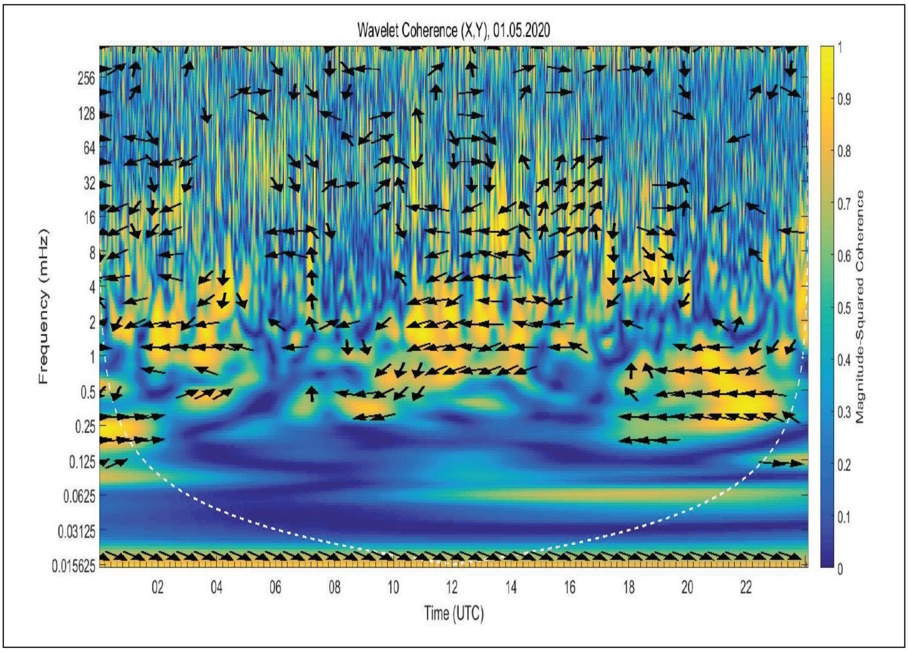

Figure 5. May1, 2020, PAG station, X and Y components

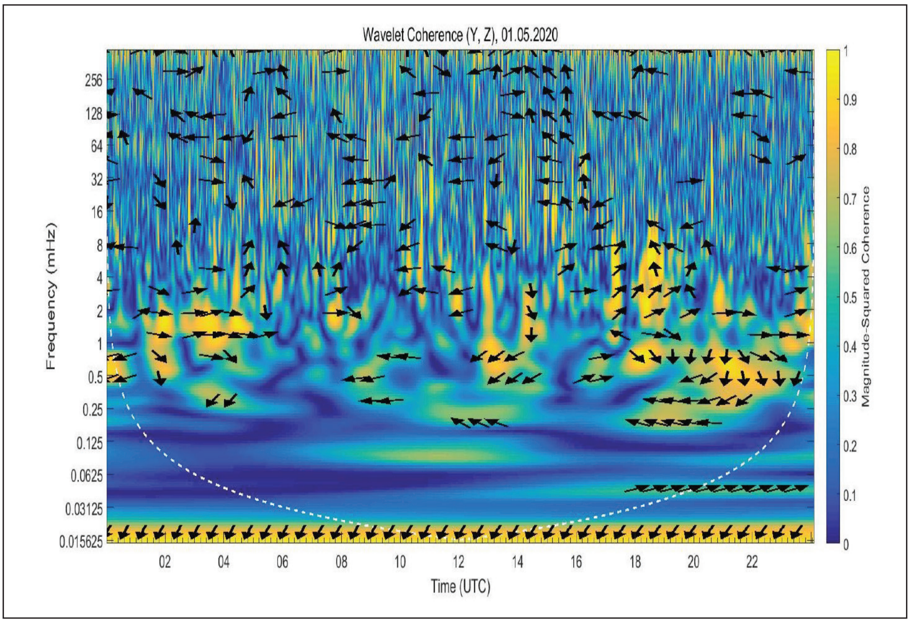

Figure 6. May1, 2020, PAG station, Y and Z components

Conclusions

On May 1, 2020, an unusual geomagnetic "noise" along the vertical (Z) component was recorded at the Geomagnetic Observatory Panagjurishte. The detrended fluctuation analysis and wavelet magnitude-squared coherence are performed, and the low levels of local and global geomagnetic activities are discussed. The specific decrease in the DFA index values calculated for the Z component in time scales 10-180 s and 10-900 s is obtained after April 29, 2020. The coherence wavelet analysis shows that on May 1, 2020, a high level of coherence between X and Z components was observed between 04 and 20 UTC. The phases of these two directions are going to differ initially, but after 11 UTC they are going to be fully synchronized. As this disturbance doesn't appear to be in the horizontal direction, it is possibly not of magnetospheric origin. The vertical direction of the disturbance cannot rule out the possibility that the cause of the disturbances on the Z component could be the preparation of the earthquake or that the observed effects are a co-seismic effect.

Acknowledgments. This work is supported by Contract No D01-404/18.12.2020 (Project "National Geoinformation Center (NGIC)" financed by the National Roadmap for Scientific Infrastructure 2017-2023.

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Изследване на ULF геомагнитен шум, записан на 1 май 2020 г. в Геомагнитна обсерватория „Панагюрище“

М. Шамати

Резюме. На 1 май 2020 г. в геомагнитната обсерватория в Панагюрище, България, необичаен геомагнитен шум на свръх-ниска честота (ULF) е записан от трикомпонентен (X, Y и Z) индукционен магнитометър. Анализирани са времевите редове от данни за периода 1 април - 1 май 2020 г. Прилагайки флуктуационен анализ с елиминиране на тренда (DFA) е изчислена DFA експонентата за времевия ред за трите геомагнитни посоки. Резултатите показват необичайно намаляване на стойностите на DFA експонентата във времевите скали 10-180s и 10-900s, което започва след 29 април 2020 г. Изчислени и определени са кохерентността и фазите на геомагнитния шум посредством Wavelet анализ, за всеки две магнитни направления, при условията на ниска геомагнитна активност. Високи стойности на кохерентност (около 0.9) в часовия интервал 04:00–20:00 UTC и пълен фазов синхрон без отместване във фазите (11:00-20:00 UTC) между компонентите X и Z се наблюдават на 1 май 2020 г., в честотния диапазон 0,125-0,25 mHz. Въз основа на извършения анализ за наблюдаваните и анализирани смущения, не може да се изключи възможността те да произхождат от литосферен източник.

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СЕИЗМИЧНОСТ НА ТЕРИТОРИЯТА НА БЪЛГАРИЯ И ПРИЛЕЖАЩИТЕ ЗЕМИ ПО ДАННИ НА НОТССИ ЗА 2022

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Абстракт. В настоящото проучване е изследвана сеизмичността през 2022 г. Представено е разпределението на епицентрите на 202 земетресения, с магнитуд M≥2.5, наблюдавани през разглеждания период на територията на България и близките околности (в периметър, ограничен от географска ширина ϕ=41° - 44.5°N и географска дължина λ=22° - 29°E), регистрирани от Националната Оперативна Телеметрична Система за Сеизмологична Информация (НОТССИ). Определени са пространствените, дълбочинни и енергетични параметри на разглежданите земетресенията. В изследвания период се наблюдават прояви в почти всички сеизмогенни зони на страната, като е отчетена най-висока активност в югозападната част от територията на България.

Ключови думи: България, земетресение, сеизмичност.

Въведение

Земетресението е природно явление, определящо се от голям брой фактори, които не могат да бъдат непосредствено наблюдавани. За сеизмично застрашените области, земетресенията представляват неделима част от околната среда. Ефектите от този тип събития са функция на редица фактори, вариращи в широки граници, които могат да бъдат адекватно моделирани въз основа на физически съображения и надеждни сеизмологични наблюдения.

Балканският полуостров е един от активните райони в Алпо-Хималайския сеизмичен пояс. Основната част от земетресенията в този район са с дълбочини до 60-70 km. Сравнително малката дълбочина на земетресенията силно увеличава степента на въздействие върху земната повърхност. Междиннофокусни събития (с дълбочина 100-200 km) се генерират само в района на Вранча и Хеленската арка. Хеленската арка се счита за сложна зона на субдукция на Африканската плоча под Евроазиатската. Голямата дълбочина на земетресенията в района на Вранча силно увеличава площта на въздействие.

България е разположена в маргиналните части на Евроазиатската континентална плоча и на Егейската микроплоча. На територията на България се намира северната граница на сеизмично активната Егейска екстензионна зона (Solakov et al., 2019). централната част на Балканския полуостров, който от тектонска гледна точка е част от континенталната граница на Евразия. Тази граница се намира между Европейския континент (Мизийска платформа) на север и офиолитовите структури (Вардар и Измир-Анкара) на юг. Неотектонските движения на Балканския полуостров са контролирани от екстензионалния колапс на късния алпийски ороген и са под влиянието, както на процесите, протичащи зад Егейската арка, така и на сложните вертикални и хоризонтални движения в Панонския регион (Solakov et al., 2019**)**. От сеизмологична гледна точка България е разположена в Алпо-Хималайския сеизмичен пояс, който се характеризира с висока сеизмична активност.

България е страна характеризираща се с умерена сеизмична активност. През вековете на територията на страната са генерирани няколко силни земетресения. Първото добре документирано земетресение на територията на България е земетресението от I в. пр.н.е. в Черно море край град Каварна. В югозападна България на 4 април 1904 г. е регистрирано и едно от най-силните плитки земетресения на територията на континентална Европа от 20- ти век (в началото на 20 век от 1901 до 1928 г. на територията на страната се реализират 6 силни земетресения с магнитуд по сеизмичен момент $M_W \geq 6.0$).

Началото на българската сеизмология датира от 1891 г. и е поставено от Спас Вацов. По това време той е директор на Централна метеорологична станция в София. Спас Вацов организира мрежа от кореспонденти за наблюдение на усетените земетресения в България (Watzof S., 1902). Периодът на българската историческа ера завършва през 1905 г., когато сеизмографът тип Omorri-Boch е монтиран в първата сеизмологична станция в град София.

Националният институт по геофизика, геодезия и география (НИГГГ) – БАН осъществява непрекъснат мониторинг на сеизмичността чрез Национална сеизмична мрежа – НОТССИ. НОТССИ е основана в края на 1980 г. В началото данните от сеизмичните станции са предавани в реално време чрез аналогови телефонни линии до центъра за данни, а параметрите на регистрираните сеизмични събития са оценявани ръчно. През 2006 г. както сеизмологичната мрежа, така и информационният център са модернизирани със съвременно цифрово оборудване и е организирана автоматична обработка на данни (Christoskov, 2019). В центъра данните се събират в реално време от 26 български станции и редица станции от съседни страни, което повишава точността на хипоцентралните оценки. Между 2005 и 2010 г. почти всички станции са модернизирани и оборудвани с широколентови сеизмометри. Данните в Националния Сеизмологичен център в НИГГГ -

БАН се предават в реално време. След това те се архивират във формат PASSCAL и допълнително в широко използваемия формат miniSEED. Данните се обработват автоматично (разпознават се съответните сигнали и се оценяват параметрите на земетресението) от програмата Seismic Network Data Processor - SNDP. През последните години броят на сеизмичните станции нараства значително и в края на 2019 г. е 40. В момента сеизмологичният център е модернизиран със софтуер SeisComP3 за реално времеви трансфер и автоматична обработка на данни, който се използва широко в сеизмологичната общност и центровете за данни (Christoskov, 2019).

Високата чувствителност на сеизмографите позволява регистриране и обработка на голям брой регионални и локални земетресения. Установени са различни по магнитуд долни прагове за надеждно определяне на регионални и локални земетресения: с магнитуд по сеизмичен момент Mw=2.5 за територията на България, Mw=3.0 за централната част на Балканите и Mw=5.0 за регионални събития.

Трябва да се отбележи, че с повишаване качеството на регистрацията на събитията, се подобрява анализа на разпределението им в пространството, времето и се предоставя възможности за прилагане на по-сложни методи като оценка на полето на напрежение (наред с други изследвания в Simeonova 2015 и Protopopova 2020) и оценка на параметрите на сеизмичния източник с помощта на спектралните характеристики (както са представени в Raykova 2019, 2020а, 2020б).

Настоящата работа съдържа обобщена информация за резултатите от обработката и предварителния анализ на изходните данни за регистрираните от НОТССИ сеизмични събития за 2022 година.

Методология при обработка на данните

Основните кинематични параметри и магнитудът на земетресенията се оценяват посредством адаптация на широко разпространения продукт HYPO‘71 (Solakov, 1993). По настоящем магнитудът Mp се определя по формулата (Christoskov et all, 2011a, b):

$$M_p = \log\left(\frac{A}{T}\right)_{max} + \sigma_{BB}\left(\Delta\right) + S_j\,, \qquad (1)$$

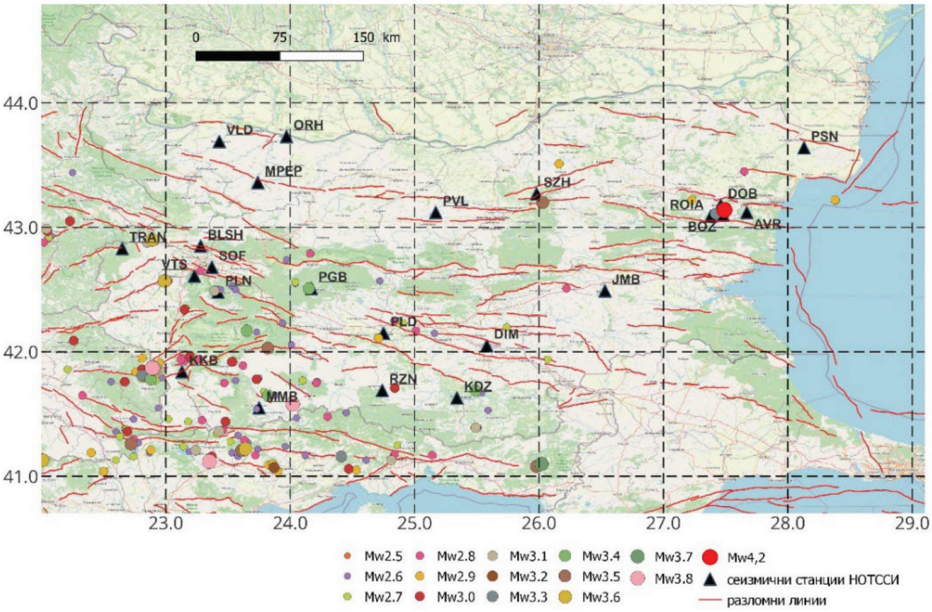
където $\left(\frac{A}{T}\right)_{max} = \frac{V_{max}}{2\pi}$, A е амплитудата в μm, T е периода в секунди (s), а v_{max} е максимална скорост в P-фазата, регистрирана на вертикалната компонента на широколентовия сеизмограф на епицентрални разстояния по-малки от 10°, $\sigma_{BB}(\Delta)$ е калибровъчна функция; и s_j е j станционна магнитудна корекция.

В настоящето изследване M_P се трансформира в по-надеждната и по-широко използвана магнитудна скала M_W, което би позволило създаването на единен и хомогенизиран каталог на земетресенията, необходим за надеждна оценка на сеизмичния хазарт на територията на страната и околностите. Магнитудът Mp се трансформира в Mw чрез формулата (Solakov et al, 2018):

$$M_w = 0.93 \times M_p + 0.31. \tag{2}$$

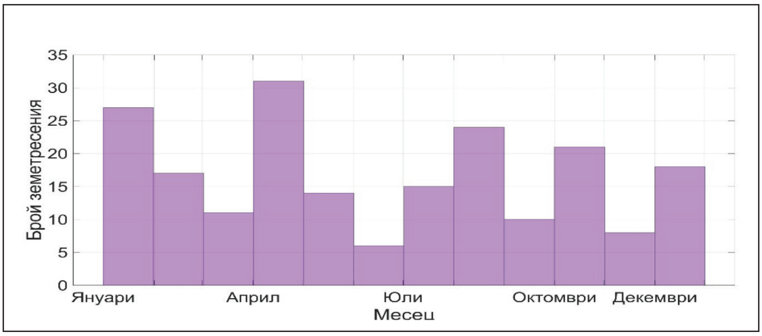
Пространствено – времево и енергетично разпределение на земетресенията

На фигура 1 е представено пространственото разпределение на епицентрите на земетресенията реализирани през 2022 г. Извадката съдържа 202 събития, в магнитуден интервал $2.5 \le M_W \le 4.5$, генерирани в пространствен прозорец с координати 41° – 44.5° N и 22° – 29° E. На картата са изобразени и активните разломи в разглежданата територия по данни от: GEM Global Active Faults (https://github.com/GEMScienceTools/gem-global-active-faults).



Фиг. 1. Епицентрална карта на земетресенията реализирани на територията на страната и прилежащите земи за 2022 г.

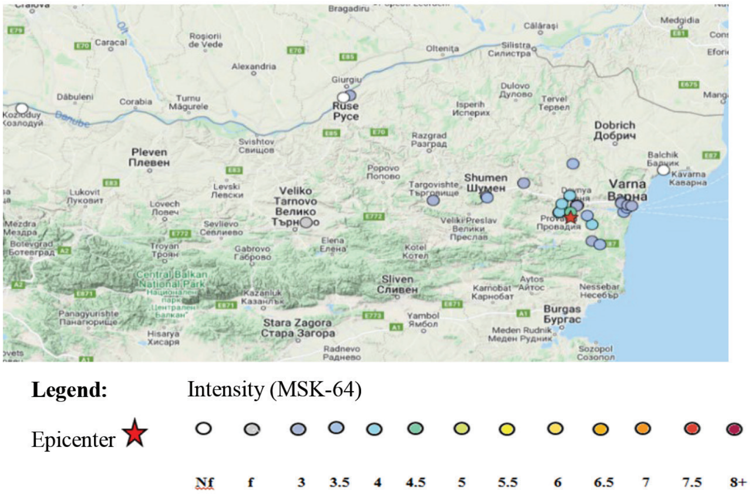
Фигура 1 илюстрира неравномерно пространствено разпределение на сеизмичността в България. Най-голяма концентрация на земетресения за 2022 г. се наблюдава в югозападния район на страната. Подробен анализ на сеизмичността в отделните сеизмични зони е трудно да се извърши поради недостатъчното количество събития и тесния магнитуден диапазон на земетресенията.



Фиг. 2. Времево разпределение на земетресенията реализирани през 2022 г. на територията на България и околностите ѝ.

Фигура 2 илюстрира разпределението на сеизмичността във времето според броя на събитията по месеци. Най-голям брой земетресения се наблюдават през месеците януари и април, а най-малко през юни и ноември.

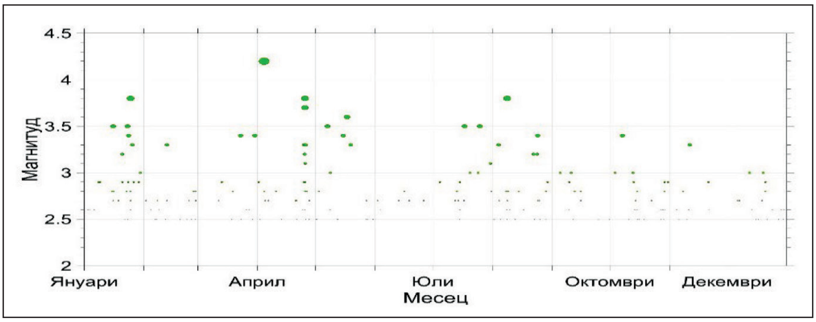
През месец април е регистрирано и най-силното за територията на България земетресение. Земетресението от 04.04.2022 г. с епицентър в близост до град Провадия. Събитието е с магнитуд M_w=4.2, дълбочината на огнището 10 km и максималната интензивност в епицентралната зона: I_{max}=4.5 степен MSK64. Земетресението е било усетено в района на град Провадия, както и във Варна, Шумен и Русе. На фигура 3 са представени въздействията от земетресението установени след обследване на засегнатата област и оценени по интензивностната скала MSK64.



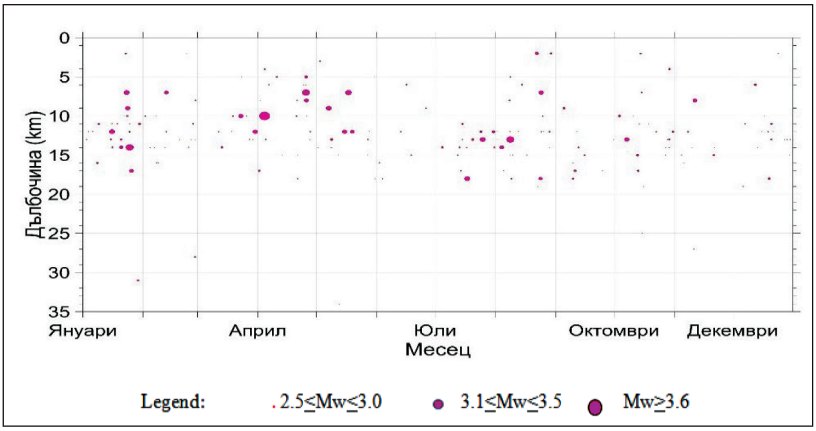
Фиг. 3. Сеизмични въздействия от най-силното за 2022 г. земетресение (M_w 4.2), реализирано на 04.04.2022 г. в близост до град Провадия.

От проследяването на магнитудите на събитията във времето представено на фигура 4 могат да се отбележат и месеците, в които са наблюдавани земетресенията с най-високи магнитудни оценки.

Броят на земетресенията групирани в магнитудни интервали: M_W = 2.5-3.0 са 161 събития, с магнитуд в интервала M_W = 3.1-3.5 са 30 събития и с магнитуд в инервала M_W = 3.6-4.0 са раелизирани 10 събития и само едно събитие с M_W = 4.2 (фиг. 4). Тук нулевото ниво трябва да се счита за относително, имайки предвид, че не са взети под внимание земетресения с магнитуди под 2.5.



Фиг. 4. Магнитудно – времево разпределение.



Фиг. 5. Разпределение на броя събития според дълбочината.

Графиката на дълбочинното разпределение на фигура 5 показва, че по-голямата част от събитията се реализират в диапазона от 5-20 км дълбочина. Броят на събитията не намалява плавно с увеличаване на дълбочината. В същото време броят на земетресенията реализирани на дълбочина 5-15 км е най-голям. Разпределението на магнитудите на събитията в дълбочина позволява да се отбележи известна диференциация на дълбочинните „етажи" с нарастване на магнитуда - максимумите могат да се проследят за интервала на дълбочината от 5 до 20 км. По-силните събития, например с магнитуд $M_W \geq 3.5$, имат дълбочина в диапазона 10-20 км. Всички огнища са разположени в земната кора.

Заключение

Територията на България, разположена в източната част на Балканския полуостров е типичен пример за район характеризиращ се с висок сеизмична опасност. През вековете на територията на страната са наблюдавани силни земетресения, като едно от тях е най-силното земетресение в континентална Европа през 20-ти век.

От представеният анализ на 202 земетресенията с магнитуд $M_W \geq 2.5$, възникнали в България и околностите през 2022г., може да се направят следните заключения:

- 2022 г. се характеризира със слаба сеизмичност - доминират събития с магнитуд под 3.0, само единадесет земетресения са с магнитуд над 3.5, като най-силното от тях е с магнитуд 4.2.
- пространствено-временното разпределение на земетресенията в България и околностите е неравномерно;
- хипоцентрите на земетресенията са разположени основно в горната кора (до 20 км). Най-голям брой земетресения са регистрирани в дълбочинния слой между 5 и 15 км;
- наблюдаваната сеизмична активност за разгледания период е по-ниска в сравнение с изминалите години. През 2022 г., са регистрирани 202 събития с магнитуд $M_W \geq 2.5$, което е по-малко сравнено с 258 регистрирани събития за 2021 г. (Popova et.al. 2021).

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SEISMICITY ON THE TERRITORY OF BULGARIA AND THE ADJACENT LANDS RECORDED BY NOTSSI IN 2022

M. Popova, E. Oynakov, Y. Milkov, V. Buchakchiev

Abstract. Spatial and temporal distribution of the seismicity observed on the Bulgarian territory in 2022 is presented. The list includes 202 earthquakes with magnitude Mw>2.5, observed in Bulgaria and the surrounding area within latitude 41°- 44.5°N and longitude $\lambda = 22° - 29°E$ which are registered by the National Operating Telemetry System for Seismological Information (NOTSSI). 2022 is characterized by weak seismicity - dominated by events of magnitude less than 3.0. Only eleven earthquakes had magnitudes larger than 3.5, the strongest of which happened on the 04.04.2022 with Mw=4.2. As observed in the previous years, the highest activity is reported in the southwestern part of the territory of Bulgaria.

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FORECASTING THE CRITICAL FREQUENCIES OF THE IONOSPHERE OVER BULGARIA IN 2022

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Abstract. The present study aims to illustrate the work in real time and in the conditions of geomagnetic storm of the developed empirical model for forecasting the critical frequencies of the ionosphere for the territory of Bulgaria. The task of creating a methodology for determining the critical frequencies is the main activity after the completion of the work of the "Plana" ionospheric station for the vertical sounding. For this purpose, a team from Department of Geophysics at the National Institute of Geophysics, Geodesy and Geography (NIGGG) – Bulgarian Academy of Sciences developed a method for determining the critical frequencies of the ionosphere based on Total Electron Content (TEC) data. The methodology allows continuing the preparation and publication of forecasts for the radio wave propagation on the territory of Bulgaria, which are used by governmental institutions and are freely available to radio amateurs through the website of the NIGGG. In the present work, a comparison is made between the critical frequencies of the ionosphere obtained by TEC for Bulgaria and the data from the vertical sounding at Rome station (RO041, 41.9°N, 12.5°E). The choice of this ionospheric station is related to the fact that this station is located at the geographic latitude coinciding with the latitude of Sofia, which suggests similar characteristics of the ionosphere. The difference in local time is also reported. The comparison between the data of the Rome ionospheric station in and those determined according to the TEC data for Bulgaria shows that the deviations are close to those obtained in the comparison with the data of Plana ionospheric station for the period 1995-2014. The described results show that the created empirical model for reconstruction of the critical frequencies by TEC data on the basis of a previous period allows predicting the current state of the ionosphere even in the conditions of geomagnetic disturbances.

Key words: Geomagnetic activity, Ionosphere, Critical frequencies, Total Electron Content, Forecasting.

Introduction

One of the main tasks related to determining the parameters of a given radio path requires the knowledge of the most essential ionospheric characteristics obtained from the ionospheric stations by the vertical sounding of the ionosphere. Due to the absence of a station for vertical sounding of the ionosphere, an empirical model has been developed (Bojilova and Mukhtarov, 2021; Mukhtarov and Bojilova, 2021a), which allows to calculate estimated values of the critical frequency of the ionospheric F region (foF2) by TEC data (Mukhtarov et al., 2021b). The method published in (Bojilova and Mukhtarov, 2021) for determining the critical frequency of the ionosphere foF2 from TEC data is based on the linear-quadratic relationship between the two ionospheric characteristics established by regression analysis. The values of TEC (which is an integral of the electron concentration by height above a certain point on the Earth's surface) are formed predominantly at heights close to the height of the maximum electron density, which uniquely determines the critical frequency. This is the maximum radio frequency that is reflected by the ionosphere during vertical propagation of radio waves. For this reason, the relationship between TEC and foF2 values turns out to be sufficiently stable and allows the critical frequency of the F region to be calculated from the TEC data with accuracy acceptable for practical purposes. The features of the diurnal and seasonal variability of the values are reflected in the model.

By comparing the measured and modeled values for the period 1995-2014, it was found that the Root Mean Square Error (RMSE) of the model foF2 values is about 0.5 MHz (Mukhtarov and Bojilova, 2021a). It is well known that the main changes in the ionosphere are related to changes in solar extreme ultraviolet, ultraviolet radiation and geomagnetic activity. It is geomagnetic activity and geomagnetic storms that cause anomalies in the variations of the elements of the Earth's magnetic field (Metodiev and Trifonova, 2021). Also these effects cause anomalies both in the ULF RANGE (Chamati, 2020; Chamati 2021a; Chamati, 2021b) and not least in the ionosphere and the radio communication frequency range (Mukhtarov et al., 2011; Mukhtarov and Pancheva, 2012, Bojilova and Mukhtarov, 2020).

Everything described so far gives reason to make a comparative analysis, illustrating the reliability of the proposed methodology for reconstructing foF2 based on TEC data for Sofia and data from the vertical sounding of the ionosphere based on Rome data. The obtained results confirm that the proposed dependency sufficiently accurately manages to solve the tasks set by the Ministry of Defense and the practical needs of environmental technologies (Lakov et al., 2018; Ivanova et al., 2018, Syrakov et al., 2013; Gadzhev et al., 2015).

Data and methods

Due to the lack of vertical sounding data on the territory of Bulgaria, in the present study a comparison was made between the modeled values of foF2 over Bulgaria with those measured at the Rome station (RO041, 41.9°N, 12.5°E). A comparison of the coordinates of this station with the coordinates of the Plana station (SQ143, 42.6°N, 23.4°E) shows that the two stations have practically the same geographic latitude with a difference in longitude 10.9°. This means that the local times at these two stations differ by 44 minutes. When comparing hourly values, this difference can be taken as one hour. The data for the ionospheric station Rome (Station Code: RO041, 41.9°N, 12.5°E) are taken from the GLOBAL IONOSPHERE RADIO OBSERVATORY (GIRO) freely available to users at the following link: https://giro.uml.edu/didbase/scaled.php. Data from GPS satellite navigation has wide application in geophysics and geodesy (Vassileva and Atanasova, 2016; Василева и Атанасова, 2016; Atanasova et al., 2021). The data for the critical frequencies over Bulgaria are calculated by an empirical model from TEC (Bojilova and Mukhtarov, 2021; Mukhtarov and Bojilova, 2021a). To solve the task of forecasting foF2 according to TEC were used data from Center for Orbit Determination in Europe (CODE) - ftp://ftp.unibe.ch/aiub/CODE/. In the examples of geomagnetic storms shown, the Kp-index is received from: Goddard Space Flight Center: https://omniweb.gsfc.nasa.gov/.

Results

In the next few examples, various comparisons are made between the data for Rome and the reconstructed data for Sofia. The purpose of this analysis is to show that the proposed methodology for reconstructing critical frequencies based on TEC data for a given past period is sufficiently good and reliable for forecasting the ionosphere over Bulgaria in real time and during geomagnetic storms.

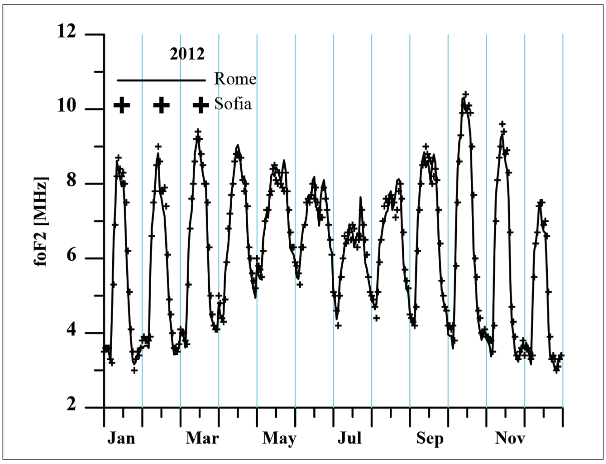

Fig. 1. Monthly medians of the critical frequency foF2 at stations SQ143 and RO041 for 2012.

Fig. 1 shows a comparison between the monthly hourly medians of the two stations for 2012. For the selected year, there are measured values from Rome- Italy and Sofia-Bulgaria. In the figure the data from Rome has been shifted by one hour, which approximately compensates for the difference in local times.

The year 2012 occupies approximately the same place in 24th Solar Cycle as 2022 occupies in the next one. As can be seen from Fig.1 the medians of the two stations are sufficiently close in value to justify the use of the Rome station data to estimate the prediction during 2022.

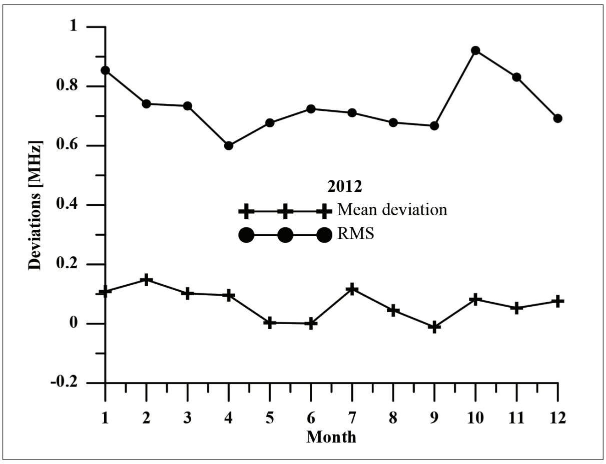

Fig. 2. Means and standard deviations between the data of stations SQ143 and RO041 for 2012.

Fig. 2 shows the mean deviation and RMSE between the SQ143 data and RO041 for each calendar month for 2012. It can be seen from Fig.2 that the mean deviation of the data from Bulgaria compared to the data from Rome for 2012 is 0.068 MHz and RMSE is 0.742 MHz. These deviations are calculated based on all hourly values for that year.

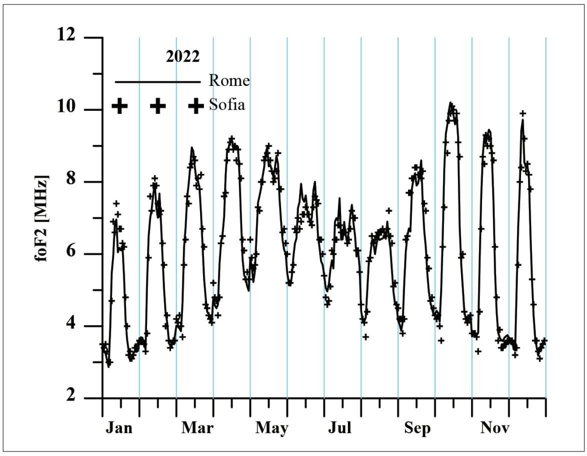

Fig. 3. Monthly medians of reconstructed critical frequency foF2 for Bulgaria and RO041 data for 2022.

Fig. 3 shows the behavior of the monthly hourly medians from the Rome ionospheric station and the reconstructed values for Sofia in 2012. The figure shows the good coincidence between the two data types. The monthly medians also show a distinct seasonal variability of foF2 characterized by lower values of critical frequencies in summer and their increase in winter conditions. The physical explanation of the obtained result is due to the so-call winter anomaly in the ionosphere. In particular, the winter anomaly is a phenomenon consisting in the fact that mid-latitude hourly median daytime foF2 value is greater in winter than in summer conditions at approximately the same solar activity level (Yasyukevich, et al., 2018).

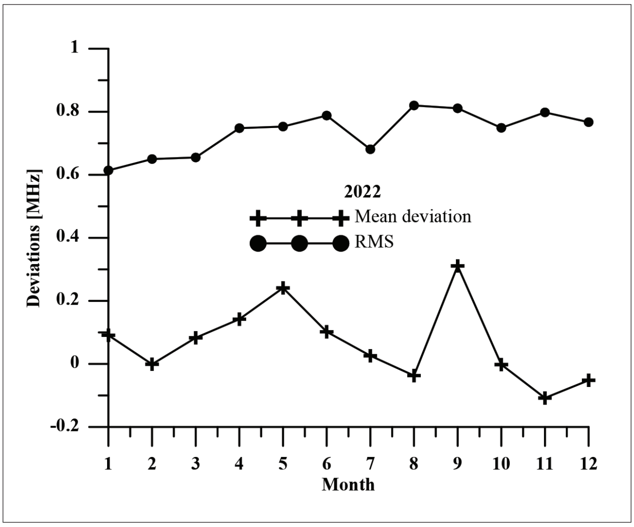

Fig. 4. Means and standard deviations between reconstructed critical frequency foF2 for Bulgaria and the measured data of RO041 for 2022.

Fig. 4 shows the behavior of the mean deviations and RMSE for each calendar month from 2022 for data from Rome and Sofia. The data for Sofia are model values derived from TEC. The mean deviation calculated on the basis of the hourly values is 0.069MHz, and RMSE is 0.741MHz. These values practically coincide with the analogous ones in 2012, which means that the deviations between the foF2 values for the two stations in both cases are dominated by the natural heterogeneity of the ionosphere and not by the inaccuracy of the reconstruction. The obtained acceptable errors give reason to analyze cases of geomagnetic storms as an additional conformation about the validity and significance of the proposed methodology for reconstructing the critical frequencies based on TEC data for the territory of Bulgaria.

The behavior of the reconstructed critical frequencies for Bulgaria compared to the critical frequencies measured in Rome during ionospheric disturbances from geomagnetic origin is shown in Fig. 5 and Fig. 6. The two disturbances in March 2022 (see Fig. 5)

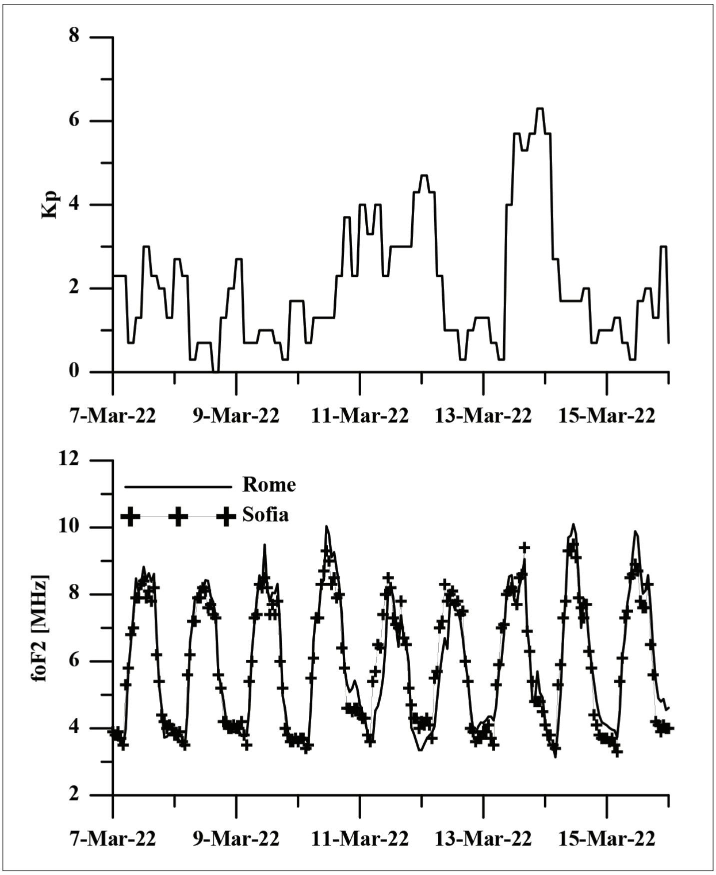

Fig. 5. Course of the reconstructed critical frequencies for Bulgaria and measured in Rome station from 7 to 15 March 2022.

and May 2022 (see Fig. 6) are relatively weak. During the first geomagnetic storm, the geomagnetic activity index Kp reaches 4 on 11 March and reached to 6 on 13 March (see Fig. 5 top panel). All this indicates that the considered geomagnetic storm is of Minor type. From Fig. 5 it follows that during the anomalies the deviation between the two types of ionospheric data increased. This phenomenon is explained in the first place by the different character of the variations in TEC and foF2 during such type of anomalies. As an integral quantity, TEC also depends on the behavior of the electron density above the maximum, which is inaccessible for vertical sounding of the ionosphere and where physical processes differ from those at lower heights (Mukhtarov and Pancheva, 2012). The different local time has an additional influence on the differences. It is well known that the ionospheric response to geomagnetic disturbances has a significant dependence on the local time (Mukhtarov et al., 2013).

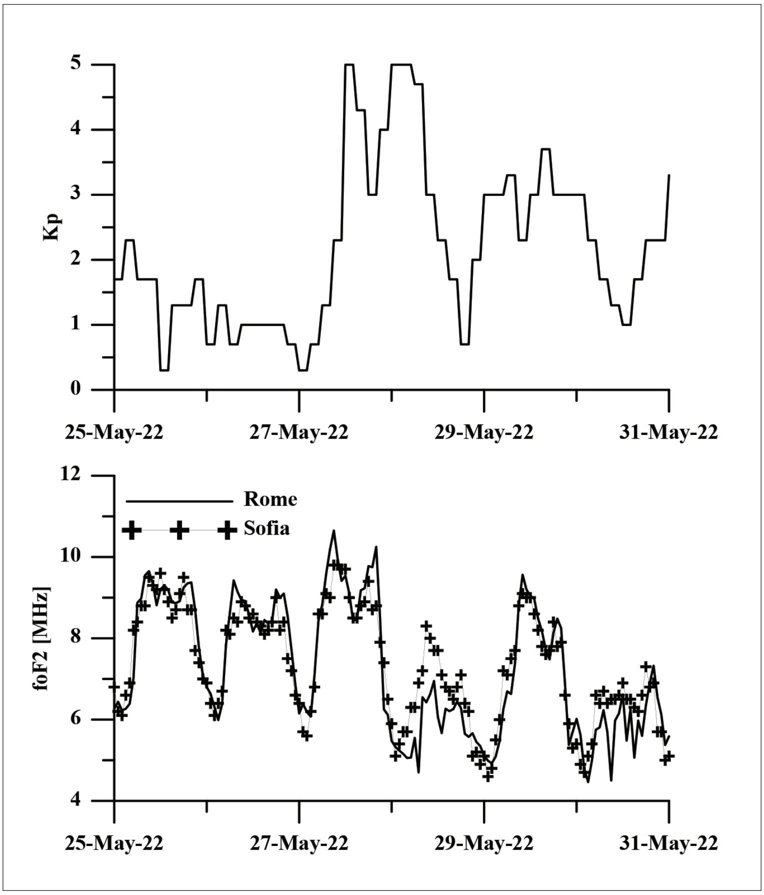

Fig. 6. Course of the reconstructed critical frequencies for Bulgaria and measured in Rome station from 25 to 30 May 2022.

In Fig. 6 shows a comparison of the behavior of the ionosphere based on data from Rome and reconstructed values for Sofia. The one shown in Fig. 6 critical frequency response illustrates the behavior of the two types of ionospheric data during the weak geomagnetic disturbance in summer conditions. From the top panel of Fig 6 it can be seen that the Kp index reaches to 5 on 27 and 28 May 2022. At the moment of the first maximum during 27 May, the critical frequencies begin to increase relative to the average, but subsequently there is a sharp decrease, which is essential for radio communications. In general, the response is predominantly negative, which is characteristic of the season during which the storm occurs. Analogous to Fig. 5 during the anomalies the deviations of both types of data increase.

Summary

In the present investigation, a comparison of the obtained model values of the critical frequency of the ionospheric F region for Bulgaria and the data of vertical sounding from the Rome ionospheric station is presented. The use of data from the Rome ionospheric station for control the forecasting of the ionosphere over Bulgaria is due to the fact that Rome station is the only nearby working station at geographic latitude coinciding with the territory of Bulgaria. The detailed analysis presented in the article of the values of the critical frequency foF2 reconstructed by TEC data for Bulgaria in 2022 shows that in the absence of data from vertical sounding of the ionosphere, the use of the empirical model for preparing radio wave propagation forecasts by TEC data is justified due to the accuracy sufficient for practical needs. A comparison of the resulting mean and RMSE errors shows that the values are of sufficiently good accuracy for practical purposes. From the comparison of the reconstructed data in 2022 with the data from the same type (by geographic location) station Rome. It is found that the differences are the same compared to the differences between the data from the vertical sounding in Sofia and Rome in 2012. The created model based on regression analysis between data from the vertical sounding and TEC for the period 1995-2014 turns out to be sufficiently accurate during the next 11-year cycle of solar activity. In addition, the behavior of foF2 during two geomagnetic storms in 2022 is considered. The presented comparison between the Rome data and the reconstructed Sofia data shows the good similarity and the clearly expressed seasonal response of the ionosphere under conditions of geomagnetic disturbances. All the obtained results show that the model created and published on the website of the National Institute of Geophysics, Geodesy and Geography for forecasting the critical frequencies based on TEC data for the territory of Bulgaria sufficiently accurately and satisfactorily manages to reconstruct and describe the behavior of the ionosphere above the country.

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Прогнозирането на критичните честоти на йоносферата над България през 2022

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Резюме: Настоящата работа има за цел да илюстрира работата в реално време и в условията на геомагнитни бури на разработения емпиричен модел за прогнозиране на критичните честоти на йоносферата за територията на България. Задачата за създаване на методика за определяне на критичните честоти е поставена след прекратяването на работата на йоносферната станция „Плана“ за вертикалното сондиране на йоносферата. За тази цел колектив от департамент „Геофизика“ при Националния институт по Геофизика, Геодезия и География (НИГГГ) към Българската академия на науките разработи метод за определяне на критичните честоти на йоносферата по данни на тоталното електронно съдържание (TEC). Методиката позволява да бъде продължено изготвянето и публикуването на прогнози за разпространение на радиовълните на територията на България които се ползват от държавни органи и са достъпни за радиолюбители посредством Интернет страницата на НИГГГ. В настоящата работа е направено сравнение между определените посредством TEC критични честоти на йоносферата за България и данните от вертикалния сондаж в станция Rome (RO041, 41.9°N, 12.5°E). Изборът на тази йоносферна станция е свързан с това, че тя се намира на географска ширина съвпадаща с географската ширина на София, което предполага близки характеристики на йоносферата. Отчетена е и разликата в локалното време. Сравнението между данните на йоносферна станция Рим и определените по TEC данни за България показва, че отклоненията са близки до тези, получени при сравнението с данните на йоносферна станция Плана за периода 1995-2014 г. Описаните резултати показват, че създаденият емпиричен модел за реконструиране на критичните честоти по данни на TEC на базата на предходен период позволява да се прогнозира и актуалното състояние на йоносферата дори и в условията на геомагнитни смущения.

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ANNUAL REPORT OF THE OBSERVED GEOMAGNETIC ACTIVITY AT PANAGJURISHTE OBSERVATORY FOR 2018

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Abstract. Magnetic variations show different records at each observatory. They depend mainly on the latitude of the observatory and the local time. This paper reports the definitive geomagnetic data obtained at Panagjurishte Observatory in 2018, prepared in the form of local geomagnetic indices and absolute time-series of daily mean values plots. 2018 is the penultimate year of Solar cycle 24, which is well into its decreasing phase (https://www.swpc.noaa.gov/products/solar-cycle-progression). It had a "double-peaked" solar maximum, with the first peak reaching a sunspot number of 99 in 2011 and the second peak in April 2014 with 101.

On the 24th of May 2018 the observatory was struck by a severe lightning storm. This damaged both systems, and they were sent out for repair. In the aftermath of this event, the observatory lost its capability to record data until the beginning of August 2018.

Calculated indices show that 2018 had 19 days with "storm"- level conditions of the geomagnetic field, but only moderate levels have been reached. The maximum K-index level reached during the period is K=6, recorded in four separate events. This weak activity is reasonable due to the fact that the sunspot numbers that year continued to decline.

Verification of data quality is performed according to "IAGA guide for magnetic measurements and observatory practice" and due to the missing data this year is labeled as "incomplete".

Key words: PAG observatory, geomagnetic variations, geomagnetic activity, local geomagnetic indices, daily mean values, 2018.

Introduction

The Geomagnetic observatory in Panagjurishte (PAG, 24.177°EN, 42.515°N) is established in 1937 – the first on the Balkan Peninsula and unique in Bulgaria and during more than 80 years performs absolute measurements of the geomagnetic field elements and continuous registration of their variations (Buchvarov, 2006). In 2007, the PAG observatory was equipped with digital systems for the recording of geomagnetic field elements' variations. Three different magnetometers are installed, which operate in a 24/7 regime: two tri-axial fluxgate magnetometers model FGE (DTU Space) – one of the standard type in which the three fluxgate sensors are mounted on a 12x12x12 cm^3 marble cube placed on a three legged aluminum base, and a second version, in which the marble cube is suspended in two crossed phosphor-bronze strips to compensate any tilt of the sensor foundation. The third instrument is a three-axial search coil magnetometer used for studies on the longitudinal propagation of ULF signal (Chamati, 2020). It provides real time measurements at a sampling period of 0.01s which are integrated at a period of 1 s.

Thus, the observatory implemented the technical requirements and was joined to the INTERMAGNET (International Real-time Magnetic Observatory Network), which establishes a global network of cooperating digital magnetic observatories, and facilitates data exchanges and geomagnetic products in close to real time. Preliminary recorded time series and local geomagnetic K-indices are published on the NIGGG web page (http://data.niggg.bas.bg/magn_data1/dailymag_bg.php) and automatically reported to INTERMAGNET. The present paper provides definitive geomagnetic data that are checked and processed to comply with the IAGA standards for observatory practices.

Local geomagnetic indices (K, A_K, ΣK) calculated at PAG observatory.

Geomagnetic irregular variations, or so called geomagnetic disturbances, are driven by the solar wind. Globally, they are evaluated by the Kp-index which is predicted and later on determined by the world data centers (Matzka et al., 2021a). It is a 3-hour quasi-logarithmic scale developed to measure magnetic activity, ranging from 0 to 9, with 0 indicating completely quiet conditions and 9 representing extreme magnetic activity. It is intended to measure geomagnetic disturbances outside the normal diurnal quiet time variations (Sq). In order to have a somewhat consistent scale of magnetic activity between observatories at high latitudes, where field variations can be quite large in amplitude, and those at low latitudes, each observatory is assigned its own set of amplitude ranges corresponding to the various K-index levels. By definition, the K-limit scales for all observatories are proportional to the Niemegk scale (Matzka, 2021b).

The eight three-hourly K numbers (after Bartels, 1939) are calculated by a computer code (FMI method, Sucksdorff et al., 1991) from the digital recordings of the three component flux-gate variometer FGE.

The local equivalent daily amplitude index ***Ak*** [nT] is determined by converting K – indices into eight 3-hour equivalent linear amplitudes a_K, and calculating the mean value. The ranges of the individual ***K*** numbers at PAG observatory and the 3-hour equivalent amplitude a_K, which is assigned for each K value, are defined in Metodiev and Trifonova, 2019. $\boldsymbol{\Sigma K}$ is the daily sum of the eight K numbers.

The calculated local geomagnetic indices (K, Ak, ΣK) at PAG observatory for 2018 are presented in Table 1.

Table 1. Local geomagnetic indices (K, A_K, ΣK) calculated at PAG observatory in 2018.

Activity Indices										
Day	K								Ak [nT]	ΣK
01-Jan-18	3	3	2	3	3	2	1	2	11	19
02-Jan-18	2	1	1	1	1	2	3	1	6	12
03-Jan-18	0	1	1	2	1	1	1	1	3	8
04-Jan-18	1	1	2	1	0	1	2	1	4	9
05-Jan-18	1	2	2	2	1	1	1	3	6	13
06-Jan-18	1	1	1	1	1	0	0	1	2	6
07-Jan-18	1	1	1	1	1	1	2	1	4	9
08-Jan-18	1	2	3	2	4	3	2	2	11	19
09-Jan-18	3	2	2	2	2	2	2	2	8	17
10-Jan-18	1	1	1	2	1	1	1	0	3	8
11-Jan-18	1	1	1	1	1	0	1	1	3	7
12-Jan-18	1	1	2	1	1	2	1	1	4	10
13-Jan-18	0	1	2	2	2	2	3	3	8	15
14-Jan-18	4	3	3	2	2	2	1	2	11	19
15-Jan-18	3	2	2	1	1	3	2	2	8	16
16-Jan-18	2	1	2	2	1	1	2	2	6	13
17-Jan-18	0	1	1	1	1	0	0	1	2	5
18-Jan-18	0	1	1	1	0	1	1	1	2	6
19-Jan-18	2	2	2	1	1	1	3	3	8	15
20-Jan-18	3	2	2	2	1	2	2	1	7	15
21-Jan-18	2	1	2	3	3	2	3	3	11	19
22-Jan-18	2	2	2	2	1	3	4	3	11	19
23-Jan-18	2	2	1	2	1	1	1	0	4	10
24-Jan-18	0	0	1	1	3	3	2	4	9	14
25-Jan-18	3	2	2	2	2	3	2	2	9	18
26-Jan-18	2	2	3	1	0	1	2	3	7	14
27-Jan-18	3	2	1	2	1	2	2	2	7	15
28-Jan-18	0	1	1	1	2	1	2	3	5	11
29-Jan-18	1	1	1	2	1	1	2	1	4	10
30-Jan-18	0	2	1	1	1	0	1	0	2	6
31-Jan-18	0	0	1	2	2	2	1	3	5	11

01-Feb-18	2	0	0	1	1	1	2	2	4	9
02-Feb-18	2	1	0	1	1	1	1	0	3	7
03-Feb-18	0	1	1	1	1	1	2	2	4	9
04-Feb-18	1	1	1	1	1	1	3	1	5	10
05-Feb-18	2	2	2	2	3	3	2	1	9	17
06-Feb-18	0	1	1	2	2	1	1	3	5	11
07-Feb-18	1	1	1	1	2	1	0	1	3	8
08-Feb-18	1	1	1	1	1	0	1	3	4	9
09-Feb-18	2	2	1	0	0	0	1	3	4	9
10-Feb-18	1	2	1	2	2	2	2	1	6	13
11-Feb-18	0	1	1	1	1	2	1	0	3	7
12-Feb-18	0	1	1	2	1	0	3	1	4	9
13-Feb-18	0	1	1	1	0	0	0	2	2	5
14-Feb-18	1	1	1	0	0	0	1	3	3	7
15-Feb-18	2	1	3	2	2	5	3	3	15	21
16-Feb-18	2	2	3	2	1	2	2	3	9	17
17-Feb-18	3	3	2	2	3	2	2	3	11	20
18-Feb-18	3	2	2	2	3	4	3	3	14	22
19-Feb-18	3	3	2	2	3	3	4	3	15	23
20-Feb-18	3	0	1	1	2	1	1	0	4	9
21-Feb-18	0	0	1	2	1	1	1	1	3	7
22-Feb-18	2	1	1	2	3	3	5	4	16	21
23-Feb-18	2	3	3	4	2	2	4	3	15	23
24-Feb-18	3	2	2	2	1	1	1	2	7	14
25-Feb-18	0	1	1	1	0	3	3	2	6	11
26-Feb-18	2	1	2	1	1	2	1	4	8	14
27-Feb-18	4	4	1	3	4	2	2	1	15	21
28-Feb-18	2	2	2	2	2	2	2	2	7	16
01-Mar-18	1	1	1	1	2	1	3	3	7	13
02-Mar-18	3	0	0	0	0	0	1	2	3	6
03-Mar-18	1	0	1	2	2	1	3	3	7	13
04-Mar-18	2	2	1	1	2	2	2	1	6	13
05-Mar-18	2	1	1	1	1	2	2	1	5	11
06-Mar-18	1	1	1	1	1	2	1	1	4	9

07-Mar-18	0	0	0	1	0	1	3	1	3	6
08-Mar-18	0	1	2	1	1	0	2	1	3	8
09-Mar-18	3	2	1	2	1	2	3	4	11	18
10-Mar-18	4	3	2	1	2	2	3	3	12	20
11-Mar-18	2	1	1	0	0	1	2	1	3	8
12-Mar-18	1	0	1	1	1	1	1	1	3	7
13-Mar-18	0	0	1	1	1	1	1	1	2	6
14-Mar-18	1	1	1	1	2	4	4	3	11	17
15-Mar-18	4	2	2	2	1	4	4	3	15	22
16-Mar-18	3	3	2	3	4	4	3	4	19	26
17-Mar-18	4	2	2	2	2	2	2	4	12	20
18-Mar-18	2	1	0	2	4	4	5	6	25	24
19-Mar-18	4	3	3	1	2	2	3	4	15	22
20-Mar-18	2	2	1	1	1	1	3	2	6	13
21-Mar-18	1	1	1	1	1	1	3	2	5	11
22-Mar-18	1	2	0	0	1	2	3	3	6	12
23-Mar-18	4	2	2	3	2	2	4	4	16	23
24-Mar-18	2	2	1	2	1	3	2	3	8	16
25-Mar-18	3	3	2	3	2	3	3	5	17	24
26-Mar-18	3	2			2	3	4	4	12	18
27-Mar-18	2	2	3	2	2	2	0	1	7	14
28-Mar-18	1	1	1	1	0	1	1	1	3	7
29-Mar-18	0	1	1	2	2	2	2	2	5	12
30-Mar-18	1	2	2	2	2	2	1	1	6	13
31-Mar-18	3	2	1	2	2	2	1	1	7	14
01-Apr-18	1	1	2	2	2	2	2	2	6	14
02-Apr-18	2	1	1	1	1	2	2	2	5	12
03-Apr-18	1	2	1	1	0	1	0	1	3	7
04-Apr-18	0	0	2	2	1	2	2	2	5	11
05-Apr-18	3	2	1	1	1	3	3	2	9	16
06-Apr-18	1	1	2	2	1	2	1	1	5	11
07-Apr-18	1	1	1	1	1	2	1	2	4	10
08-Apr-18	1	1	1	1	0	1	3	3	6	11
09-Apr-18	1	1	2	2	2	3	3	5	13	19
10-Apr-18	2	3	3	3	3	3	3	4	16	24

11-Apr-18	4	2	2	1	2	1	2	2	9	16
12-Apr-18	1	2	2	2	2	2	3	3	9	17
13-Apr-18	4	1	2	1	1	1	3	4	11	17
14-Apr-18	2	1	0	2	2	2	2	2	6	13
15-Apr-18	2	1	1	1	1	1	1	3	5	11
16-Apr-18	1	1	1	1	0	0	0	2	2	6
17-Apr-18	2	1	1	0	0	1	1	2	3	8
18-Apr-18	1	1	1	2	2	3	2	1	6	13
19-Apr-18	0	0	1	2	0	1	1	1	2	6
20-Apr-18	4	3	5	5	3	4	6	4	36	34
21-Apr-18	3	2	2	2	2	4	3	2	12	20
22-Apr-18	1	1	1	1	2	1	1	1	4	9
23-Apr-18	3	1	1	1	1	1	3	3	8	14
24-Apr-18	0	1	1	2	2	2	3	2	6	13
25-Apr-18	2	2	1	1	1	0	0	2	4	9
26-Apr-18	2	1	1	1	1	1	1	2	4	10
27-Apr-18	2	1	2	2	1	3	2	2	7	15
28-Apr-18	2	1	1	1	1	1	1	0	3	8
29-Apr-18	0	1	2	2	2	2	1	1	5	11
30-Apr-18	2	2	1	1	2	2	2	0	5	12
01-May-18	0	1	1	1	1	0	1	1	2	6
02-May-18	2	2	1	2	1	1	1	1	5	11
03-May-18	1	1	1	2	1	1	2	2	5	11
04-May-18	1	0	1	1	1	1	2	2	4	9
05-May-18	1	1	2	4	4		5	5	20	22
06-May-18	5	3	3	3	3	3	4	4	22	28
07-May-18	4	3	3	2	3	3	2	3	15	23
08-May-18	2	3	2	2	2	4	4	2	13	21
09-May-18	3	2	2	2	2	2	4	3	12	20
10-May-18	3	2	2	2	2	3	2	3	10	19
11-May-18	1	3	4	1	3	2	4	4	16	22
12-May-18	2	3	1	2	1	2	2	3	8	16
13-May-18	1	2	2	2	3	3	3	3	11	19
14-May-18	1	1	1	2	1	1	1	2	4	10
15-May-18	0	2	1	1	1	2	2	2	5	11

16-May-18	0	0	0	1	1	1	2	2	3	7
17-May-18	3	2	2	3	2	2	2	3	10	19
18-May-18	2	1	1	2	1	1	1	1	4	10
19-May-18	1	1	1	1	1	1	2	1	4	9
20-May-18	1	2	1	1	1	1	0	0	3	7
21-May-18	0	1	1	1	1	0	0	1	2	5
22-May-18	0	1	1	2	2	2	2	2	5	12
23-May-18	2	3	2	3	2	2	1	2	9	17
04-Aug-18	1	2	1	1	1	1	1	1	4	9
05-Aug-18	1	2	1	2	2	2	1	2	6	13
06-Aug-18	1	2	1	1	1	1	2	1	4	10
07-Aug-18	2	3	2	2	3	2	3	2	10	19
08-Aug-18	1	1	1	2	2	2	2	1	5	12
09-Aug-18	2	1	2	2	1	1	1	1	5	11
10-Aug-18	2	2	1	1	1	2	1	1	5	11
11-Aug-18	2	2	3	2	3	2	3	4	13	21
12-Aug-18	2	1	1	2	2	2	2	2	6	14
13-Aug-18	1	1	1	2	1	1	1	2	4	10
14-Aug-18	1	0	0	2	1	1	0	1	2	6
15-Aug-18	2	1	2	3	3	3	4	3	13	21
16-Aug-18	4	2	1	3	3	2	2	2	11	19
17-Aug-18	3	3	2	2	1	1	3	4	12	19
18-Aug-18	2	3	3	2	2	3	2	2	10	19
19-Aug-18	2	2	1	1	1	3	3	3	9	16
20-Aug-18	3	3	2	2	3	3	4	2	14	22
21-Aug-18	3	1	2	2	1	1	1	2	6	13
22-Aug-18	2	1	2	1	2	2	1	3	7	14
23-Aug-18	2	1	1	0	1	1	1	2	4	9
24-Aug-18	0	1	1	2	3	1	1	1	5	10
25-Aug-18	1	2	3	3	3	2	4	4	15	22
26-Aug-18	5	6	5	4	5	5	5	3	45	38
27-Aug-18	2	2	2	3	4	5	5	3	22	26
28-Aug-18	4	2	2	2	2	1	1	1	8	15
29-Aug-18	3	2	1	1	1	2	2	2	7	14
30-Aug-18	1	1	1	1	0	0	2	3	4	9

31-Aug-18	1	1	1	2	1	2	3	1	6	12
01-Sep-18	1	1	1	1	2	1	3	2	6	12
02-Sep-18	2	2	1	2	1	2	2	2	6	14
03-Sep-18	1	1	1	2	2	2	2	3	7	14
04-Sep-18	1	2	2	1	2	2	3	3	8	16
05-Sep-18	3	2	1	2	3	2	2	1	8	16
06-Sep-18	2	1	2	1	1	1	2	2	5	12
07-Sep-18	2	2	2	1	1	1	1	1	5	11
08-Sep-18	1	0	3	2	0	1	1	2	5	10
09-Sep-18	2	1	2	1	2	2	2	3	7	15
10-Sep-18	0	1	1	1	2	5	5	5	20	20
11-Sep-18	4	4	5	5	3	3	4	3	28	31
12-Sep-18	2	1	1	2	1	3	3	4	10	17
13-Sep-18	4	3	3	3	3	3	2	3	16	24
14-Sep-18	3	2	2	2	2	2	4	4	13	21
15-Sep-18	2	1	2	2	2	1	1	3	7	14
16-Sep-18	1	2	2	2	1	1	1	2	5	12
17-Sep-18	2	2	2	2	2	3	4	3	12	20
18-Sep-18	3	1	1	2	0	1	1	1	5	10
19-Sep-18	1	2	2	1	1	1	0	0	3	8
20-Sep-18	0	1	1	1	1	0	0	0	2	4
21-Sep-18	0	1	1	1	1	1	2	4	6	11
22-Sep-18	5	3	3	3	4	3	4	4	24	29
23-Sep-18	3	2	1	2	3	2	3	3	11	19
24-Sep-18	3	2	2	2	1	2	2	2	8	16
25-Sep-18	2	2	1	3	3	3	4	3	13	21
26-Sep-18	1	1	1	1	2	3	2	3	7	14
27-Sep-18	1	1	1	2	2	1	1	3	6	12
28-Sep-18	3	2	2	1	0	1	1	3	7	13
29-Sep-18	3	2	2	2	3	2	2	3	10	19
30-Sep-18	1	2	1	1	1	1	2	2	5	11
01-Oct-18	0	1	1	2	4	3	3	3	11	17
02-Oct-18	3	2	2	1	1	1	3	0	7	13
03-Oct-18	1	1	1	2	1	1	2	3	6	12
04-Oct-18	2	1	0	1	2	2	2	2	5	12

05-Oct-18	2	2	2	3	3	2	1	3	10	18
06-Oct-18	3	1	1	1	1	1	0	0	4	8
07-Oct-18	0	1	1	3	4	5	5	5	24	24
08-Oct-18	3	3	3	2	4	4	2	2	15	23
09-Oct-18	3	1	3	3	3	4	3	4	17	24
10-Oct-18	3	1	1	2	3	4	6	3	21	23
11-Oct-18	3	2	1	2	2	3	3	2	10	18
12-Oct-18	1	2	1	2	1	2	2	3	7	14
13-Oct-18	1	2	1	1	3	5	5	3	18	21
14-Oct-18	2	1	1	2	1	2	2	3	7	14
15-Oct-18	3	2	1	2	2	3	3	3	11	19
16-Oct-18	2	0	1	2	2	2	1	1	5	11
17-Oct-18	0	1	1	1	0	0	0	0	1	3
18-Oct-18	0	0	1	1	1	0	1	0	2	4
19-Oct-18	0	1	1	1	1	0	1	1	2	6
20-Oct-18	0	0	1	1	1	1	1	1	2	6
21-Oct-18	0	1	1	2	2	2	2	2	5	12
22-Oct-18	3	1	1	1	2	2	2	2	7	14
23-Oct-18	1	1	1	2	1	1	0	1	3	8
24-Oct-18	1	1	1	2	0	1	2	2	4	10
25-Oct-18	1	2	1	1	1	3	3	3	8	15
26-Oct-18	2	2	1	2	1	1	3	3	8	15
27-Oct-18	1	1	2	1	0	0	0	0	2	5
28-Oct-18	2	0	1	1	0	0	1	1	2	6
29-Oct-18	0	1	1	1	0	1	1	1	2	6
30-Oct-18	1	1	1	1	0	1	1	1	3	7
31-Oct-18	1	0	0	1	1	2	2	2	4	9
01-Nov-18	1	1	2	2	1	1	1	2	5	11
02-Nov-18	3	0	1	2	1	1	1	1	5	10
03-Nov-18	2	2	1	1	1	0	1	2	4	10
04-Nov-18	1	1	2	2	1	3	5	5	17	20
05-Nov-18	4	4	4	4	3	4	5	3	27	31
06-Nov-18	2	3	1	2	2	2	1	2	7	15

07-Nov-18	2	2	2	1	1	1	3	3	8	15
08-Nov-18	3	3	2	3	1	1	2	2	9	17
09-Nov-18	1	1	1	2	1	3	4	4	11	17
10-Nov-18	2	2	2	4	2	2	4	4	15	22
11-Nov-18	3	2	1	1	1	1	3	2	7	14
12-Nov-18	2	2	2	2	2	1	3	3	9	17
13-Nov-18	2	1	1	2	1	1	1	1	4	10
14-Nov-18	0	1	1	1	1	1	2	1	3	8
15-Nov-18	0	0	1	2	0	1	0	1	2	5
16-Nov-18	1	1	1	1	1	1	0	0	2	6
17-Nov-18	1	1	1	2	0	0	0	0	2	5
18-Nov-18	0	1	0	1	1	1	1	2	3	7
19-Nov-18	2	1	1	2	0	2	1	3	6	12
20-Nov-18	2	3	2	1	0	2	1	1	6	12
21-Nov-18	2	3	2			0	0	1	4	8
22-Nov-18	1	0	2		1	1	1	1	3	7
23-Nov-18	1	1	1	1	0	0	1	1	2	6
24-Nov-18	1	1	1	1	1	2	2	2	5	11
25-Nov-18	1	1	1	2	1	1	0	1	3	8
26-Nov-18	1	1	0	1	0	0	0	1	2	4
27-Nov-18	1	1	1	1	2	2	3	2	6	13
28-Nov-18	1	1	0	1	1	1	1	2	3	8
29-Nov-18	2	0	0	1	0	0	0	2	2	5
30-Nov-18	1	0	1	0	0	0	1	0	1	3
01-Dec-18	0	1	1	2	2	4	4	2	10	16
02-Dec-18	2	1	1	2	2	4	3	4	12	19
03-Dec-18	2	1	1	2	3	3	3	2	9	17
04-Dec-18	4	2	2	2	4	3	2	2	13	21
05-Dec-18	2	1	2	1	2	1	1	3	6	13
06-Dec-18	2	2	2	1	2	1	1	1	5	12
07-Dec-18	1	2	2	2	2	3	4	3	11	19
08-Dec-18	2	2	2	2	2	3	2	2	8	17
09-Dec-18	2	1	2	2	2	3	3	4	11	19

10-Dec-18	2	2	3	2	2	2	2	1	8	16
11-Dec-18	1	2	2	3	1	3	3	2	9	17
12-Dec-18	2	1	1	1	1	1	2	1	4	10
13-Dec-18	0	1	0	1	1	1	0	0	2	4
14-Dec-18	1	0	1	1	0	1	0	1	2	5
15-Dec-18	1	0	1	1	1	1	1	0	2	6
16-Dec-18	1	0	1	1	1	1	1	1	3	7
17-Dec-18	1	2	2	2	1	2	3	2	7	15
18-Dec-18	2	1	1	1	2	2	3	1	6	13
19-Dec-18	2	2	2	2	1	2	2	2	7	15
20-Dec-18	3	2	2	2	1	2	3	3	10	18
21-Dec-18	2	1	2	1	1	0	2	1	4	10
22-Dec-18	1	1	1	1	1	0	1	1	3	7
23-Dec-18	1	0	1	1	1	0	1	1	2	6
24-Dec-18	1	1	1	1	1	0	1	2	3	8
25-Dec-18	1	2	1	1	1	1	2	2	5	11
26-Dec-18	0	0	1	1	2	1	1	0	2	6
27-Dec-18	1	1	0	1	1	1	2	3	5	10
28-Dec-18	4	3	4	3	4	3	5	3	24	29
29-Dec-18	2	2	2	2	3	2	3	3	10	19
30-Dec-18	2	2	2	2	2	3	3	1	9	17
31-Dec-18	3	1	1	1	2	1	1	1	5	11

Geomagnetic disturbances and local K-index.

In Table 2 are given days with K-indices equal to or larger than 5 which means geomagnetic storm conditions. Indices above the “threshold” value are marked in red. For 2018, there are 15 days with K-index ≥ 5 and 4 days with K-index ≥ 6 . In addition, for the time period when the observatory was not functioning, there was one day with storm conditions, as shown by the planetary K index – Kp. According to the data for the Kp index from the Word Data Center for Geomagnetism, Kyoto such a day was the 1st of June, 2018 when Kp-index=5 was obtained (https://wdc.kugi.kyoto-u.ac.jp/kp/index.html) .

Table 2 Days with K-index ≥ 5 registered in 2018 at the Panagjurishte observatory**Error! Not a valid link.**

DD-MM-YY	00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24	Ak [nT]	ΣK
15-Feb-18	2	1	3	2	2	5	3	3	15	21
22-Feb-18	2	1	1	2	3	3	5	4	16	21
18-Mar-18	2	1	0	2	4	4	5	6	25	24
25-Mar-18	3	3	2	3	2	3	3	5	17	24
09-Apr-18	1	1	2	2	2	3	3	5	13	19
20-Apr-18	4	3	5	5	3	4	6	4	36	34
05-May-18	1	1	2	4	4		5	5	20	22
06-May-18	5	3	3	3	3	3	4	4	22	28
26-Aug-18	5	6	5	4	5	5	5	3	45	38
27-Aug-18	2	2	2	3	4	5	5	3	22	26
10-Sep-18	0	1	1	1	2	5	5	5	20	20
11-Sep-18	4	4	5	5	3	3	4	3	28	31
22-Sep-18	5	3	3	3	4	3	4	4	24	29
07-Oct-18	0	1	1	3	4	5	5	5	24	24
10-Oct-18	3	1	1	2	3	4	6	3	21	23
13-Oct-18	1	2	1	1	3	5	5	3	18	21
04-Nov-18	1	1	2	2	1	3	5	5	17	20
05-Nov-18	4	4	4	4	3	4	5	3	27	31
28-Dec-18	4	3	4	3	4	3	5	3	24	29

In Fig. 1, the annual mean values of D [min], I [min], H [nT], X [nT], Y [nT], Z [nT] and F [nT] registered at PAG observatory from 1948 up to 2018 are plotted. The increasing trend is maintained in an almost linear form and a constant gradient

Conclusions

Continuous registration of the geomagnetic field components gives the sum of all field contributions from internal and external (to the Earth) sources. A straightforward separation of the individual contributions is impossible, and many scientific studies deal with different aspects of this problem (Mandea nad Korte, 2010). Furthermore, there are also effects from additional sources which could influence the magnetic records such as thunderstorms (Chamati and Andonov, 2021).

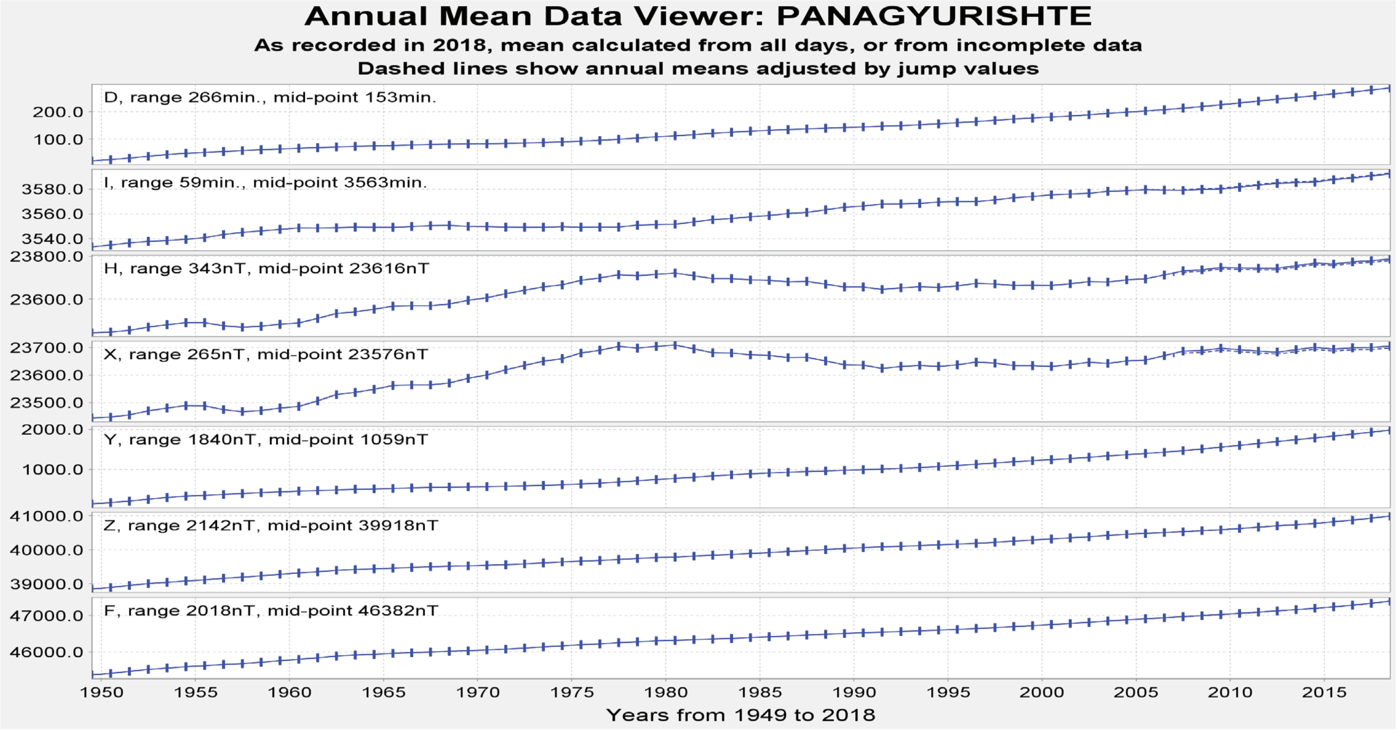

Fig. 1. Annual mean values of D [min], I [min], H [nT], X [nT], Y [nT], Z [nT] and F [nT] registered at the PAG observatory from 1948 up to 2018.

An approximate description of the strength of different external variations, however, is provided by geomagnetic indices. A quantitative measure of 2018 local geomagnetic activity in the form of a 3 hour *K*-index is published here, based upon the range of fluctuations in the PAG observatory records. Table 2 shows that the number of data values having disturbed the geomagnetic field in 2018 is decreasing to 19 (+1 for the period where the Observatory was not functioning). For comparison, in 2017, there were 50.

The most active period began on August 26 and ended on August 27. The strongest events during 2018 were on March 18 and August 26 with the largest K-index 6. The observed activity is quite reasonable because 2018 is already at the tail end of the 24th Solar cycle.

The data are checked and verified according to IAGA requirements (Jankowski and Sucksdorff, 1996).

The secular trend of declination (D), inclination (I), horizontal (X and Y), and vertical (Z) field components, as well as the total field intensity measurement at Panagjurishte observatory up to 2018, is plotted in the next figure:

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Годишен доклад за наблюдаваната геомагнитна активност в Обсерватория Панагюрище през 2018

М. Методиев, П. Трифонова

Резюме: Записите на магнитните вариации показват различни стойности и поведение във всяка обсерватория. Те зависят основно от географската ширина на обсерваторията и местното време.

Тази статия представя окончателните геомагнитни данни, получени в обсерватория Панагюрище през 2018 г., изготвени под формата на локални геомагнитни индекси. През 2018 г. Слънчевият цикъл 24 вече е към своя край (https://www.swpc.noaa.gov/products/solar-cycle-progression). Той се характеризира с двоен слънчев максимум, като при първия пик е достигнат брой на слънчевите петна 99 през 2011 г., а във втория пик през април 2014 г. броят на петната е 101.

Изчислените индекси показват, че през 2018 г. има 19 дни с условия, определящи ниво „буря“ на геомагнитното поле, но са достигнати само умерени нива. Само за четири дни, на 18 Март, 20 Април и 26 Август и 10 Октомври 2018 г. е изчислен К-индекс 6. Това е очаквано и разбираемо поради факта, че броят на слънчевите петна през тази част от Слънчевия цикъл продължава да намалява.

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COMPARISON OF FOUR EARTHQUAKE DECLUSTERING METHODS APPLIED TO THE HOMOGENEOUS EARTHQUAKE CATALOG FOR BULGARIAN AND ADJACENT REGIONS (1981-2019)

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Abstract. Composite Abstract: The spatial-temporal distribution of seismic activity in Bulgaria and adjacent regions was studied using a homogeneous earthquake catalog from 1981 to 2019. The catalog comprised 1024 earthquakes with $Mw \geq 3.2$, collected from the Bulgarian Seismological Network. To isolate primary and secondary shocks and background events, four declustering methods were employed: Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhammer (1986). The catalog consists of earthquakes in Bulgaria and the surrounding areas (41° – 44°.6N, 22° – 30° E; 1024 events), with a completeness magnitude $Mc = 3.2$. After declustering, the number of events in the final catalogs varied for each method. The cumulative distribution was analyzed, and mainshocks, foreshocks, and aftershocks were identified for specific events. The study emphasized the importance of declustering in seismic analysis but recognized limitations in data completeness, quality, and algorithmic constraints. The results provided valuable insights for seismologists and specialists studying seismic phenomena and seismic risk assessment.The methods were applied using the ZMAP software

Keywords: Catalog, declustering, completeness

Introduction

The spatial-temporal distribution of seismic activity and tectonics in Bulgaria, as well as in various parts of the world, have been statistically and physically studied by many authors, and some significant results have been obtained (e.g. Solakov, Simeonova, 1993, Boncev et al., 1982, Utsu 1971, Habermann 1983, Frohlich and Davis 1993, Wiemer and Wyss 2000, Ambraseys 2002, Kutoglu and Akcin 2006, Kutoglu et al., 2008,). Bulgaria has a well-defined fault network and established seismicity history. The territory of the country is a high seismic risk zone (I. Aleksandrova, et al., 2018). Over the centuries, Bulgaria has experienced strong earthquakes (Watzof, 1902, Shebalin et al, 1974 and other). In the early 20th century (from 1901 to 1928), five earthquakes with a magnitude greater than or equal to $M_S \geq 7.0$ occurred in Bulgaria (Solakov D., et al., 2011). However, after 1928, no damaging events occurred in Bulgaria, which may cause non-professionals to underestimate the risk of earthquakes. The earthquake in 1986 with a magnitude of Mw = 5.6, which occurred in central northern Bulgaria (near the town of Strazhitsa, studied in Oncescu et al., 1990), is the strongest event of the 20th century after 1928. In 2012, a moderate earthquake with a magnitude of Mw = 5.6 and an epicenter between the towns of Pernik and Radomir caused moderate to severe damage in the epicentral zone. In addition to seismic activity in the Balkans, earthquakes in Greece and Turkey have an impact on the region. Declustering the earthquake catalog is an essential step in analyzing seismic activity as it allows for the separate identification of mainshocks, foreshocks, and aftershocks. This is achieved by removing dependent and repeating events that are characteristic of seismic regimes. Mainshocks are events with higher magnitude and serve as a starting point for analyzing seismic activity in the region. Identifying them is crucial as they provide information about the primary seismic events that can lead to significant destruction and risks to the population and infrastructure.

Data

The database used in this study is taken from the presented homogeneous earthquake catalog for Bulgaria and adjacent regions, covering the period from 1981-2019 (Solakov D., Simeonova S., Raykova Pl., Aleksandrova I., 2020; D. Solakov et al., 2020). The catalog includes instrumental seismicity (Solakov et al. (1993) and Botev et al. (2010)), covering the time interval from 1981-2000, which was updated for the period 2001-2019 using instrumental earthquake parameters. The earthquake data in the catalog is from the Bulgarian Seismological Network (NOTSSI). Currently, the Bulgarian Seismological Network provides reliable registration and high-quality information on earthquakes in Bulgaria and its surroundings (Christoskov et al. (2019). The catalog has been processed by removing duplicate events and quarry blasts. The comprehensive assessment of the catalog's completeness shows that no earthquake with a seismic moment magnitude of Mw 3.2 or higher has been missed during the entire instrumental period (1981-2019) (Solakov D. et al., 2020). The catalog includes 1024 earthquakes with a magnitude of $Mw \geq 3.2$ that occurred in Bulgaria between 1981 and 2019 (Figure 1).

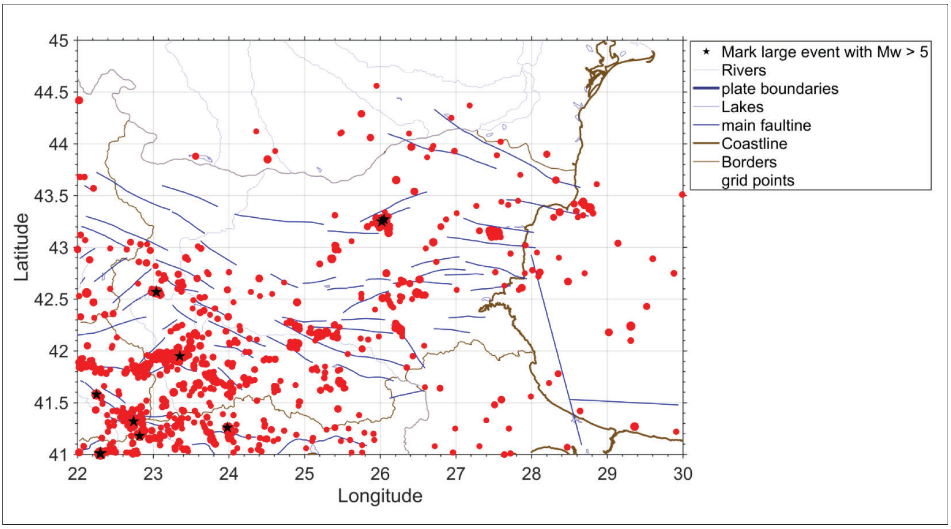

Figure 1. Map of the spatial distribution of earthquake epicenters from the catalog of Bulgaria (1981-2019).

The applied seismic moment magnitude (Mw) contributes to more reliable results and does not require the calculation of new empirical values of a different magnitude type.

Used methods

There are four main methods, Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhamer (1986), for removing dependent events from the catalog. Each takes into account a different range of distance and time.

Gardner-Knopoff (1974) Method:

This method is based on the concept that aftershocks tend to cluster around the mainshock in both time and space. It uses two separate windows to determine whether an event is an aftershock or part of the background seismicity. The first window is a time window that measures the interval between an earthquake and its potential mainshock, while the second window is a spatial window that measures the distance between the event and the mainshock. If an event falls within these windows, it is considered an aftershock and is removed from the catalog as a dependent event.

Gruenthal (pers. Comm.) Method:

The Gruenthal method is based on the concept of earthquake clustering and uses a probabilistic approach to identify aftershocks. It considers both time and distance parameters but uses a different formulation compared to Gardner-Knopoff. The Gruenthal method defines specific mathematical expressions for time and distance windows, which depend on the magnitude of the mainshock. Similar to the Gardner-Knopoff method, events falling within these windows are classified as aftershocks and excluded from the catalog.

Reasenberg (1985) Method:

The Reasenberg method is another widely used declustering algorithm. It uses a probabilistic approach and defines specific parameters such as minimum and maximum future time for cluster creation, confidence level, effective minimum magnitude limit, and iteration radius factor. The algorithm calculates a future time window based on these parameters and identifies events that fall within this window as aftershocks. The Reasenberg method is considered more robust and flexible, as it allows for adjustments of various parameters to tailor the declustering process to different seismic regions.

Urhamer (1986) Method:

The Urhamer method is based on the concept of using statistical laws to separate aftershocks from background seismicity. It employs exponential decay curves to model aftershock sequences and defines specific distance and time parameters for the declustering process. Similar to the other methods, events that fit the aftershock model are removed from the catalog.

The standard input parameters for the Reasenberg (1985) declustering algorithm are given in Table 1, are as follow:

- τ_{min} is the minimum future time for cluster creation when the first event is not clustered;
- τ_{max} is the maximum future time for cluster creation;
- 'Confidence Level' is the probability of detecting the next clustered event, used to calculate the future time – τ;
- 'hk factor' is the increase in the lowest magnitude limit during clustering: xmeff = xmeff + xkM, where M is the magnitude of the largest event in the cluster; xmeff (Effective min mag cutoff) is the effective minimum magnitude limit for the catalog;
- 'Iteration radius factor' is the number of crack radii around each earthquake considered part of the cluster;
- 'Epicenter error' is the error in determining the coordinates of the earthquake epicenters in km;
- 'Depth error' is the error in determining the depths of earthquake hypocenters in km.

Table 1. Standard and limiting parameters for Reasenberg (1985) - declustering algorithm.

Parameter	**Standard value**	**Modeling scope**	
		minimum	**maximum**
τ_{min} [days]	1	0.5	2.5
τ_{max} [days]	10	3	15
Confidence Level	0.95	0.9	0.99
Effective min mag cutoff	4.0	0	10
xк factor	0.5	0.1	1.8
Iteration radius factor	10	5	20
Epicenter error	1,5	-	-
Depth error	2	-	-

Table 2 presents the approximate sizes of the windows, which are determined by Gardner and Knopoff (1974), Gruenthal (pers.comm.), and Uhrhammer (1986).

Table 2. Approximate sizes of windows according to Gardner and Knopoff (1974), Gruenthal (pers.comm.) and Uhrhammer (1986).

Method	**Distance (km)**	**Time (days)**
Gardner and Knopoff (1974)	$10^{0.1238M+0.983}$	$10^{0.32M+2.7389}.\, jf\ M \geq 6.5$ $10^{0.5409M-0.547}.else$
Gruenthal (pers.comm.)	$10^{1.77+(0.037+1.02M)^2}$	$\left\| e^{-3.95+(0.62+17.32M)^2} \right\|, if\ M \geq 6.5$ $10^{2.8+0.024M}.else$
Uhrhammer (1986)	$e^{-1.024+0.804M}$	$e^{-2.87+1.235M}$

After declustering with these four methods, the maximum and minimum number of events are those of Reasenberg and Gruenthal methods, respectively. In this article, these basic methods are used to decluster the catalog, and the results of these methods are compared.

Results

After declustering using the methods of Gruenthal, Reasenberg (using standard input parameters), Gardner and Knopoff, and Uhrhammer, the catalog contains 730, 899, 790, and 863 events, respectively (Table 3).

Table 3. Number of events by different methods implemented in ZMAP Software.

Method	Number of events	Number of clusters	Number of foreshocks	Number of aftershocks	Events remaining in the catalog
Reasenberg (1985)	1024	22	20	105	899
Gardner and Knopoff (1974)		43	38	196	790
Gruenthal (pers.comm.)		60	76	218	730
Uhrhammer (1986)		23	20	141	863

One commonly used parameter for characterizing the recording capability of the seismic network is the magnitude completeness (Mc), which is understood as the magnitude above which earthquakes are recorded with a probability close to 1. Having detailed knowledge of the spatial and temporal variations of Mc is critical for many earthquake hazard studies as they assess the statistical properties of microseismicity. Such estimates can only be meaningful if the sampled earthquake catalogs contain complete records of microseismicity events. For example, studies on earthquake distribution or seismicity rates heavily depend on knowledge of Mc (e.g., Wiemer & Wyss 2002; Schorlemmer et al. 2005). The magnitude-frequency distribution of each algorithm is presented in Figure 2.

The cumulative distribution after each algorithm is presented in Figure 3. There is no significant change in the graph and cumulative functions (Fig. 3) until December 7, 1986, when an earthquake with hypocentral parameters 43.230 N/26.020 E; h=14 km Mw=5.6 occurred near the town of Strazhitsa (northern Bulgaria). The earthquake was accompanied by foreshocks and aftershocks series, which appeared as a jump on the cumulative curve graph of the non-declustered catalog (purple line) appeared as a jump. The next jump in the cumulative curve of the catalog is in May 2009 due to the foreshocks and aftershocks accompanying the earthquake of May 24, 2009, with Mw=5.3 near Lake Doiran, Republic of North Macedonia (22.740/41.320E; h=5 km).

The resulting number of events after declustering the catalog (Table 3) shows that the Reasenberg method have a maximum number of events, while the Gruenthal method have a minimum number of events.The map of mainshocks identified by the different methods is shown in Fig. 4. The events identified as mainshocks by all the methods used are 5 (Table 4) and (Fig. 4), while seven events are identified as mainshocks by three of the methods (Gruenthal, Reasenberg, Knopoff). The Knopoff and Gruenthal methods identify 29 common events, the Gruenthal method compared to Reasenberg identifies 10 common events, and Knopoff compared to Reasenberg identifies 9 common main events. Six are foreshocks identified by all four methods, 9 foreshocks are identified simultaneously by all methods; 105 for the methods of Knopoff, Gruenthal, Urhammer; 169 are common to the methods of Knopoff and Gruenthal (fig. 6).

Table 4. Earthquakes identified as mainshock by the four methods.

Longitude	Latitude	Year	Monht	Day	Magnitude	Depth	Hour	Minute
25,41	42,98	2000	8	28	4,2	10	5	16
22,11	41,85	2009	5	5	4,1	7	17	39
23,28	41,96	2013	7	27	4	2	1	48
26,24	42,23	2015	4	2	3,5	11	2	27
22,82	41,18	2018	1	2	5,1	9	4	24

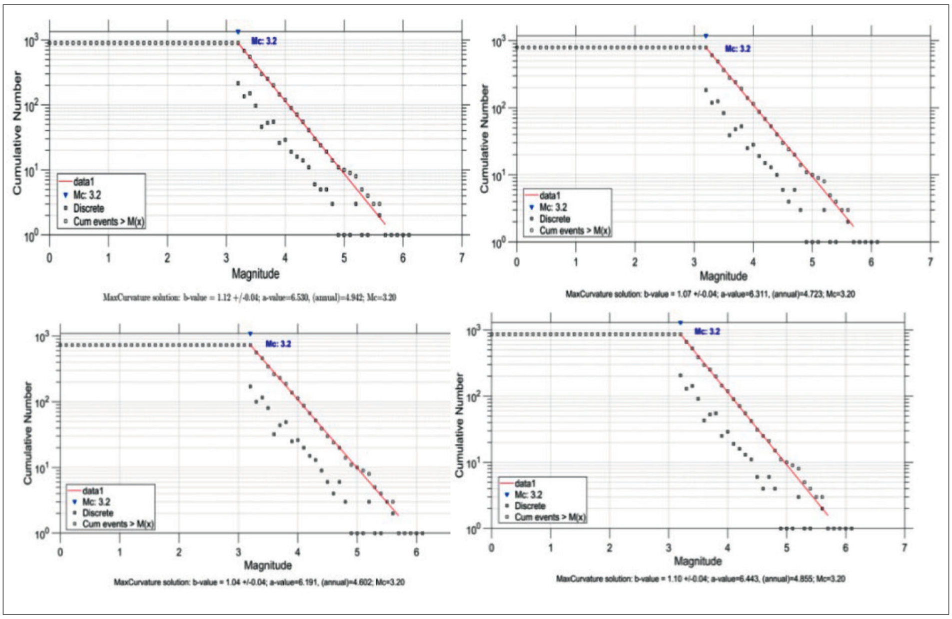

Figure 2. Magnitude-frequency distribution of declustered catalogs a) Knopoff, b) Urhammer, c) Reasenberg, and d) Gruenthal

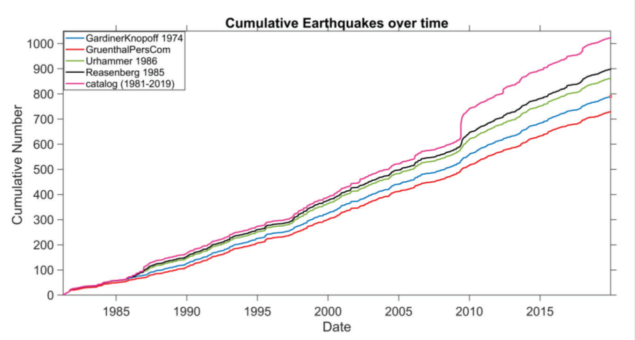

Figure 3. The cumulative distribution of earthquakes after each algorithm applied over the catalog (1981-2019).

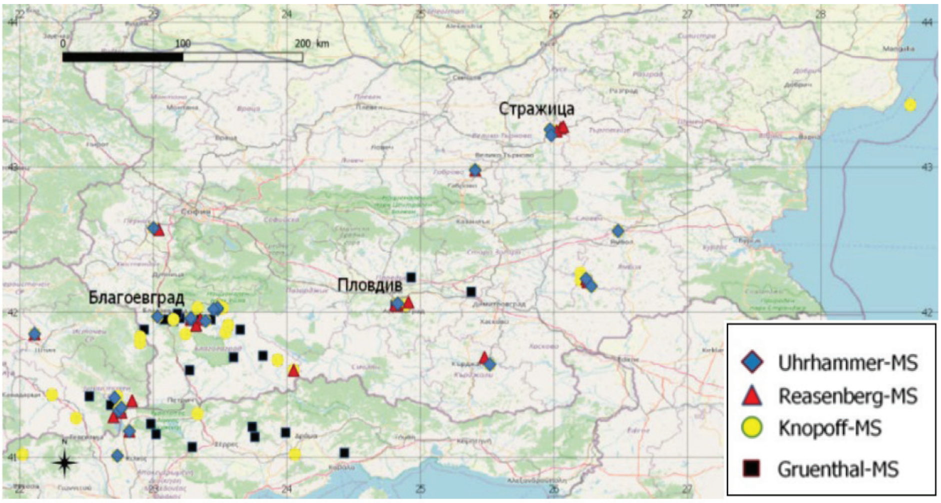

Figure 4. Map of the distribution of earthquake epicenters determined as mainshocks (MS) by each of the methods.

Figure 5. Map of the distribution of the epicenters of earthquakes determined as foreshocks (FS) according to each of the methods.

The number of earthquakes with different magnitudes, after declustering with the methods, is shown in Fig. 7. In this region, there are no events with a magnitude greater than 5.6 for the studied period (1981-2019).Two strongest and well-studied events are particularly important for the assessment of the methods, as indicated in the introduction, namely: near Strazhitsa in July 12, 1986; 14:17; h=14 km; Mw=5.6 and near Pernik in May 22, 2012; 14:00; h=14km; Mw=5.6.

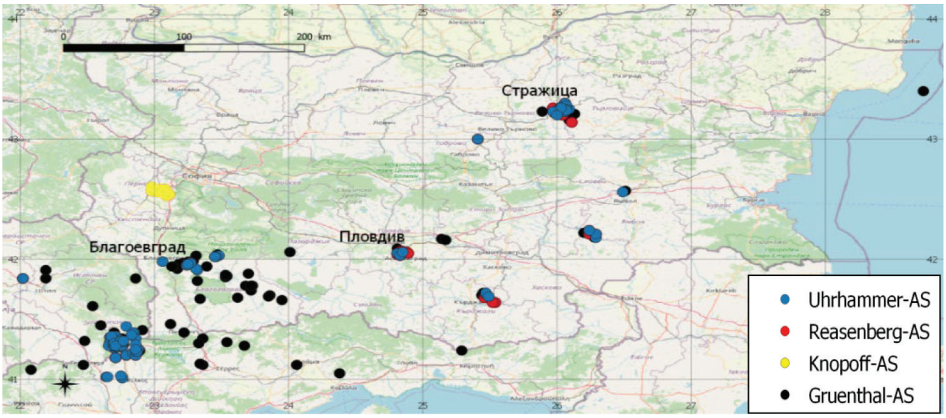

Figure 6. Map of the distribution of earthquake epicenters determined as aftershocks (AS) according to each of the methods.

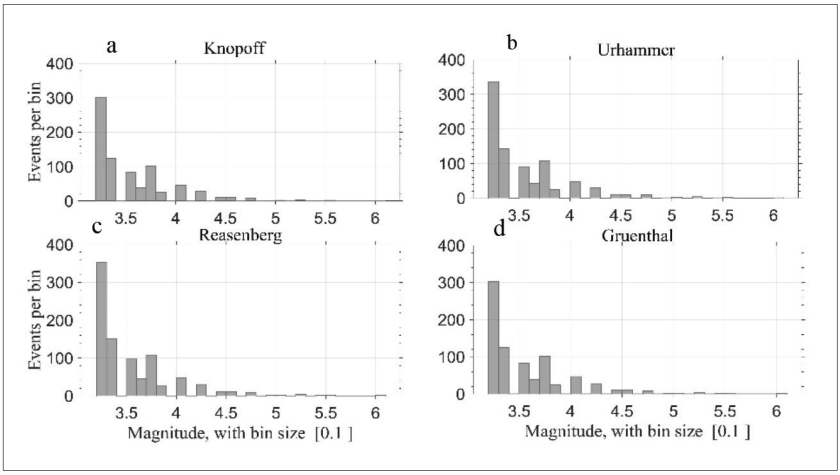

Figure 7. Distribution of earthquakes by magnitude after declustering using the methods of a) Knopoff, b) Urhammer, c) Reasenberg, and d) Gruenthal.

Figure 8 shows a map of the epicenters of earthquakes determined as foreshocks, mainshocks, and aftershocks by the four methods for the earthquake of July 12, 1986; h=14km; Mw=5.6. The review of the results shows that for the period from February 1, 1986 to December 30, 1986, the Gruenthal algorithm detects 2 mainshocks, Knopoff-1, Reasenberg-3, and Urhammer-1, with the Urhammer algorithm not identifying the earthquake of July 12, 1986; 14:17 hours; h=14 km; Mw = 5.6 as a mainshock. The Gruenthal and Urhammer algorithms identify 14 and 2 events, respectively, as foreshocks. As aftershocks, the methods identify 16 for Gruenthal, 16 for Knopoff, 12 for Reasenberg, and 13 for Urhammer. The results are shown both on the map (Figure 8) and in tabular form in Table 5.

Table 5. Results of earthquake declustering in the area of Strazhitsa for the period from February 1, 1986, to December 30, 1986.

Longitude	**Latitude**	**Year**	**Monht**	**Day**	**Magnitude**	**Depth**	**Hour**	**Minute**	**Gr.**	**Kn.**	**Re.**	**Ur.**
26,05	43,27	1986	2	21	5,4	11	5	39			🟥	
25,97	43,26	1986	2	21	4,4	16	6	18	🟨	🟥	🟦	🟥
25,99	43,23	1986	2	21	3,5	18	6	20	🟨		🟦	
26,02	43,26	1986	2	21	3,8	15	8	36	🟨		🟦	
25,62	43,06	1986	3	23	3,2	12	20	50	🟨			
26,13	43,18	1986	4	10	3,2	0	4	43	🟨			
26,01	43,21	1986	5	25	3,3	14	16	57	🟨			
26,03	43,24	1986	5	26	3,2	13	15	46	🟨			
26,07	43,25	1986	6	20	3,4	10	12	26	🟨			
26,06	43,27	1986	8	1	3,4	11	14	34	🟨			
25,99	43,19	1986	8	19	4	13	4	5	🟨			
26,06	43,34	1986	8	29	3,2	11	19	30	🟨			
26,01	43,23	1986	9	7	3,3	13	10	47	🟨			
26	43,26	1986	9	7	3,3	12	10	54	🟨			
26,01	43,25	1986	11	23	3,4	9	4	34	🟨			
26,02	43,25	1986	12	7	5,6	14	14	17	🟥	🟥	🟥	
26,11	43,14	1986	12	7	4,4	20	14	53	🟦	🟦	🟦	🟨
26,04	43,2	1986	12	7	3,3	2	15	20	🟦	🟦	🟦	🟨
25,98	43,22	1986	12	7	4,8	14	17	26	🟦	🟦	🟦	🟥
25,98	43,22	1986	12	7	3,2	13	17	39	🟦	🟦	🟦	🟦
26,06	43,3	1986	12	8	3,3	13	9	31	🟦	🟦	🟦	🟦
26,03	43,26	1986	12	8	4,5	20	14	44	🟦	🟦	🟦	🟦
26,04	43,24	1986	12	11	3,4	15	3	52	🟦	🟦		🟦
26,09	43,25	1986	12	12	3,6	10	1	28	🟦	🟦		🟦
26,05	43,27	1986	12	12	4,6	12	19	29	🟦	🟦		🟦
26,02	43,24	1986	12	14	3,2	10	10	29	🟦	🟦		🟦
26,03	43,27	1986	12	15	3,4	6	0	58	🟦	🟦		🟦
26,07	43,28	1986	12	17	4,8	14	22	1	🟦	🟦	🟥	🟦
26,06	43,23	1986	12	18	4,4	14	7	16	🟦	🟦	🟦	🟦
26,07	43,25	1986	12	18	4,5	18	17	16	🟦	🟦	🟦	🟦
26,07	43,25	1986	12	18	3,6	11	23	39	🟦	🟦	🟦	🟦
26,07	43,24	1986	12	23	3,2	6	17	46	🟦	🟦		🟦

🟨 **- foreshock** 🟥 **- mainshock** 🟦 **- aftershock**

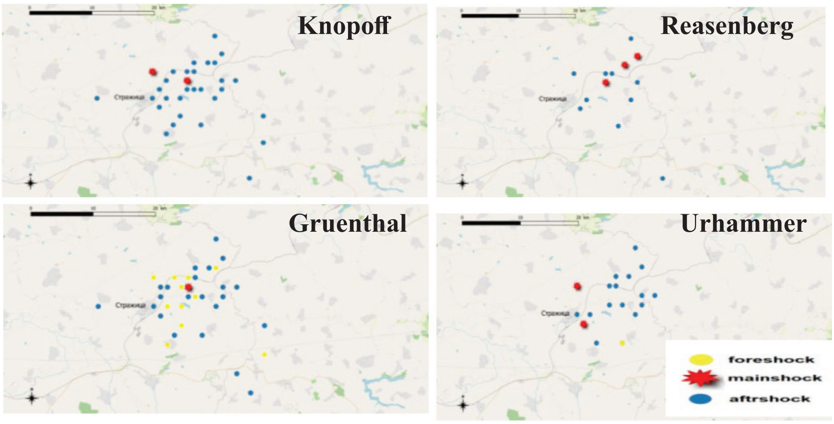

Figure 8. Maps of the epicenters of the events defined as foreshocks, mainshocks, and aftershocks for the region of Strazhitsa for the period from February 1, 1986, to December 30, 1986.

Figure 9. Maps of the epicenters of the events defined as foreshocks, mainshocks, and aftershocks in the Pernik region for the period from 22.05.2012 to 03.09.2012.

The results of the different methods for the earthquake in the vicinity of Pernik on May 22, 2012 at 14:00 with a depth of 14 km and Mw=5.6 are shown on the maps in Fig. 9 and presented in tabular form in Table 6

The results show that for the period from 22.05.2012 to 03.09.2012, the Gruenthal algorithm detects 1 mainshock, Knopoff detects 1, and Urhammer detects 1, and all three do not identify the earthquake on 22.05.2012 at 00:00 hours; h=14 km; Mw=5.6 as a mainshock. The Gruenthal, Knopoff, and Urhammer algorithms identify 3 events as foreshocks. As for aftershocks, the methods determine as follow: Gruenthal - 16, Knopoff - 15, Reasenberg - 12, and Urhammer - 13.

Table 6. Results of declustering for the earthquake in the area of Pernik for the period from 22.05.2012 to 03.09.2012.

Longitude	**Latitude**	**Year**	**Monht**	**Day**	**Magnitude**	**Depth**	**Hour**	**Minute**	**Gr.**	**Kn.**	**Re.**	**Ur.**
23,04	42,57	2012	5	22	5,6	14	0	0			🟥	
22,98	42,57	2012	5	22	4,3	4	0	4	🟨	🟨	🟦	🟨
23,08	42,56	2012	5	22	3,2	17	0	16	🟨	🟨	🟦	🟨
23,05	42,58	2012	5	22	3,6	10	0	43	🟨	🟨	🟦	🟨
23	42,58	2012	5	22	4,8	13	1	30	🟥	🟥	🟦	🟥
23,09	42,53	2012	5	22	3,2	10	1	34	🟦	🟦	🟦	🟦
22,98	42,6	2012	5	22	3,4	11	2	11	🟦	🟦	🟦	🟦
23,07	42,58	2012	5	22	4,3	12	2	13	🟦	🟦	🟦	🟦
23,04	42,57	2012	5	22	3,4	2	4	9	🟦	🟦	🟦	🟦
23,08	42,58	2012	5	22	3,3	15	4	29	🟦	🟦	🟦	🟦
23,04	42,58	2012	5	22	3,5	17	17	7	🟦	🟦	🟦	🟦
23,11	42,54	2012	5	23	3,2	11	10	57	🟦	🟦	🟦	🟦
23,02	42,56	2012	5	23	3,3	2	11	41	🟦	🟦		🟦
23,09	42,56	2012	5	23	3,9	14	21	59	🟦	🟦	🟦	🟦
23,01	42,58	2012	5	29	3,9	8	7	23	🟦	🟦		🟦
23,07	42,55	2012	5	30	3,6	9	5	36	🟦	🟦		🟦
23,07	42,57	2012	6	16	3,2	10	4	51	🟦	🟦		🟦
23,06	42,57	2012	7	14	4,4	8	12	52	🟦	🟦		🟦
23,1	42,54	2012	7	31	3,4	7	0	10	🟦	🟦		
23,06	42,57	2012	8	16	3,3	10	2	11	🟦	🟦		
22,91	41,41	2012	9	3	3,2	4	16	54	🟦			

🟨 **- foreshock** 🟥 **- mainshock** 🟦 **- aftershock**

Conclusion

For comparison of the declustering algorithms of Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhammer (1986), the homogenized catalog 1981-2019 of the earthquakes occurred in the region of Bulgaria and adjacent areas are used. The this catalog is a summary of the time of occurrence of the earthquake, geographic coordinates, magnitude, and depth for each presented event. The Wiemer ZMAΠ (2001) package including the algorithms is used to remove duplicate events, aftershocks. Before declustering, the catalog has 1024 events. After declustering with the algorithms of Gardner-Knopoff, Gruenthal, Reasenberg, and Urhammer, the final catalogs include respectively 790, 730, 899, and 863 main events from 1981 to 2019.

The sequences of fore- and aftershocks reflect local anomalies of the seismic regime and significantly differ in their characteristics from the background regime. The dependence on the degree of declustering of the catalog is given by estimates of the parameters of the seismic process. To isolate fore- and aftershocks from all background events, the algorithms of Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985), and Urhammer (1986) are used, which are based on comparing the functions of time and spatial distribution. The procedure for identifying primary and secondary shocks is reduced to constructing a discriminant function that allows each earthquake to be classified into one of three classes: primary and secondary shock or background event. From a physical point of view, the difference between primary, secondary shock, and background event is not obvious; all procedures for identifying accompanying events are based on statistical laws, i.e., on the spatial-temporal localization of aftershocks in the vicinity of the main event.

When identifying primary and secondary shocks, three types of errors are possible: assigning a primary or secondary shock to a group of background or main events, identifying a background event as a primary or secondary shock, and identifying a main event as a primary or secondary shock.

Research based on the data used for seismic events may encounter limitations regarding the completeness, accuracy, and reliability of the obtained results. Here are some of these limitations:

Data Completeness: The used data may not include all seismic events, particularly those that were weak or unreported. The presence of data gaps can restrict the analysis and lead to incomplete or distorted results.

Data Quality: Data on seismic events can be subject to various sources of error, such as sensor issues or data transmission disruptions. This can affect the accuracy and reliability of the obtained results.

Geographical Coverage: The coverage of seismic monitoring in different regions can vary. Some areas may have limited data or be poorly represented in the catalog. This can hinder comprehensive analyses and generalizations about global seismic activities.

Algorithmic Limitations: The computational procedures and software algorithms used for data analysis may have their own limitations. They may be perceived as model-based or approximate methods that do not always reflect a complete and precise representation of seismic activity.

Human Interpretation: Data processing and analysis can involve human interpretation and subjective decisions. This can lead to variations and inconsistencies in the results, particularly in complex cases or ambiguous events.

It is important to bear these limitations in mind.

The fact that the catalog is compiled using statistical data and computational procedures with specialized software for seismic event analysis, such as ZMAP, is highly important information. This means that the catalog has been created through the processing of a large amount of data collected from various seismic sources and sensors.

The use of statistical data and computational procedures is a valuable approach for analyzing seismic data, as it can help identify patterns and trends in seismic activity. The utilization of specialized software like ZMAP further enhances the capabilities for processing and analyzing this data.

Such a catalog can be extremely beneficial for seismologists, geologists, and other specialists studying seismic phenomena. They can utilize this catalog for analyzing seismic events, investigating the geographical distribution of earthquakes, assessing the risk of seismic activities, and other related activities.

This is a good practice that contributes to a better understanding of seismic phenomena and improves our ability to forecast and respond to potential hazards associated with them.

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Сравнение на резултататите, получени по четири метода за деклъстеризиране на земетресения, приложени върху хомогенния каталог на земетресенията за българия и съседните райони (1981-2019)

Е.Ойнаков, И. Александрова, М. Попова

Резюме. Съществуват различни методи за деклъстеризация на каталози от земетресения и тяхното хомогенизиране. Reasenberg (1985) и Gruenthal са известни като методи, които генерират каталог с максимален и минимален брой събития, съответно. В това проучване са приложени четири основни метода за деклъстреризиране (Gardner-Knopoff (1974), Gruenthal (pers. Comm.), Reasenberg (1985) и Urhamer (1986)) върху каталога на земетресенията за периода 1981-2019 г., (Solakov D., et al, 2020). Каталогът се състои от земетресения в България и околностите (41° – 44°, 6 N, 22° – 30°E; 1024 събития), с магнитуд на пълнота Mc=3.2. Методите са приложени с помощта на софтуера ZMAP.

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SEISMIC TOMOGRAPHY MODEL OF EARTH CRUST OF SW BULGARIA AND SURROUNDINGS

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Abstract. The paper deals with the tomography investigations of the earth's crust inhomogeneity of the SW Bulgarian area and its geodynamic features. The main aim is to reveal the relationships of the seismic tomography model and the crustal inhomogeneity's structures located at SW Bulgaria and surroundings. This aim is strongly related with the seismic activity of the region, where strong earthquakes in Kresna-Kroupnik (M7.2 and M7.8, 1904), Valandovo (M6.7, 1931) and Skopje (M6.1, 1963) with a lot of destructions and victims occurred. There are also other less active seismic sources as Velingrad, Mesta, Struma, etc. with lower seismic potential. The seismic tomography model, calculating the velocity residuals for P and S seismic waves from the optimal velocity model helped to establish the possible reasons for the geodynamic features of the region. Discovered velocity anomalies coincide pretty well with the previously investigated geophysical anomalies (velocities' depth changes, asthenosphere gradients, thermal conductivity, fluids saturation, etc.) and geodynamic features (fracturing, faults, grabens and horsts, crustal movements, etc. The local seismicity is also considered, showing higher concentrations of hypocenter near the established velocity gradient areas. The performed tests about the accuracy of the calculations and ongoing interpretation helped to increase the reliability of the results obtained.

Kay words: earthquake, seismicity, tomography

Introduction

The Southwest Bulgaria geology and geodynamics have a complex structure and complicated mixture of different in time development and size elements: grabens and horsts, lowlands and river beds, high mountain peaks and small and larger structures and blocks, separated by faults and morphology features. The most important geodynamic peculiarities of the area are high seismic activity of different type, vertical crustal movements and intensive erosion.

Seismic tomography uses seismic ray inversion and velocity models to reveal inhomogeneity in deep layers, reflecting local and regional features of the Earth's interior Studying the deviations in the velocity at different depths of the P and S seismic waves, are possible to outline anomalies in wave's propagation. This could be a powerful tool to reveal the specific geodynamic structures as blocks, faults and structure boundaries at different depths.

The focus of this tomography study is the SW Bulgaria and surroundings because this area has specific seismic regime – strong earthquakes in Kresna-Kroupnik (1904), Valandovo (1931) and Skopje (1963) with a lot of destructions and victims and other less seismic active sources as Velingrad, Mesta, Struma, etc. with lower seismic potential (Ranguelov et al., 2001). So, the geodynamic study of the area needs a specific approach combining information of seismic tomography with the geodynamic and seismic regime of the region.

Data

Data from 1700 local and regional earthquakes registered by 64 seismic stations located from 19°-31°E/35°-46°N and processed by the national operative telemetric seismological system (NOTSSI) of Bulgaria for the time interval 01.01.2016 to 31.12.2021 (fig. 1) were used in the study. The total number of travel times from the sources to the seismic stations is 47487 of which 32927 are of P-phase and 14560 of S-phase seismic

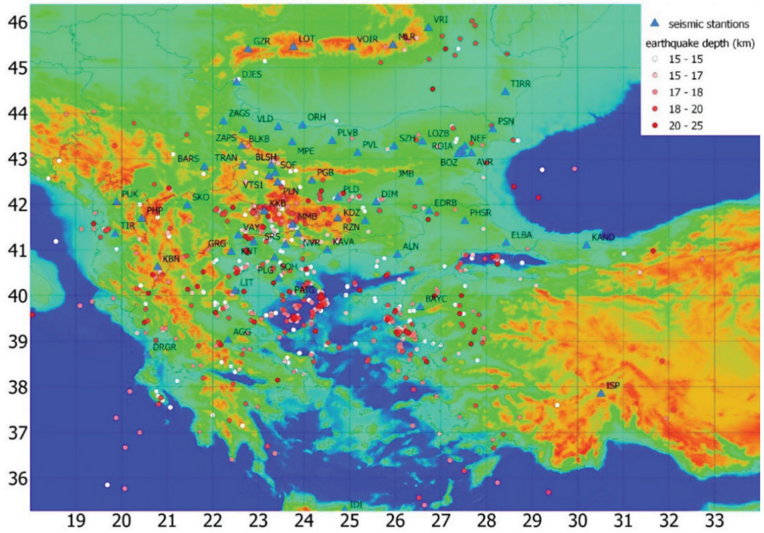

Fig. 1. Map of recorded local and regional earthquakes by NOTTSI for the time interval 01.01.2016 to 31.12.2021

waves. The minimum number of arrivals for each event is 10, thus ensuring high accuracy. At the source pre-localization stage, some of the arriving waves with residuals larger than 1.5 seconds for P and 2 seconds for S waves were rejected for higher reliability.

Method

The methodology includes several steps of the algorithm – Tomography inversion, 1D velocity model optimization, 3D visualization and results presentation.

- Tomographic inversion is performed based on the LOTOS 12 nonlinear passive seismic tomography algorithm. The general principles and technical details are described [Kulakov, 2009] and on the website www.ivan-art.com/science/LOTOS (Fig. 2). The LOTOS-12 computer code performs the simultaneous inversion of P- and S-wave velocities and source and stations' coordinates. The algorithm can be applied to various local earthquake data sets without complicated parameterization.
- In the initial stage of the computations, simultaneous optimization of the best one-dimensional velocity model and preliminary source localization is performed. The distribution providing the minimum value of the mean residuals was selected as the reference model for further tomographic modelling.
- The iteration procedure starts with the step of localization of the seismic sources in a three-dimensional model (at the first iteration, this algorithm is applied to a one-dimensional reference model). One of the features of this algorithm is the three-dimensional ray tracing, which is based on the bending method (Um, Thurber, 1987) using Fermat's principle for minimizing the time functional described in (Koulakov, 2009). This algorithm is used at each step of the iterative inversion, in the localization of the sources and is resulting in a three-dimensional model of the strata.

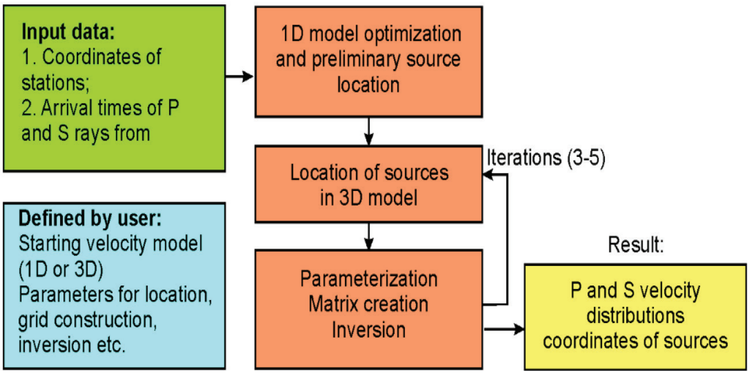

Fig. 2. Block diagram of the algorithm of tomography inversion (Koulakov, I. (2013). Code LOTOS-10 for 3D tomographic inversion is based on passive seismic data from local and regional events.)

- The matrix of first derivatives (M.R. Fréchet matrix), in addition to the P- and S-velocity distributions, includes elements needed to correct the coordinates and timing in the source (4 parameters for each source) and station corrections. The matrix inversion is performed using the LSQR method (Paige, Saunders, 1982; van der Sluis, van der Vorst, 1987).
- When performing inversion, the problem of weighting individual parameters with different dimensions (velocity distribution, source parameters and station corrections) as well as determining the smoothing parameters arises. In this study, this procedure is performed by applying synthetic tests with realistic noise in the data, providing similar inversion conditions as in the case of real data.

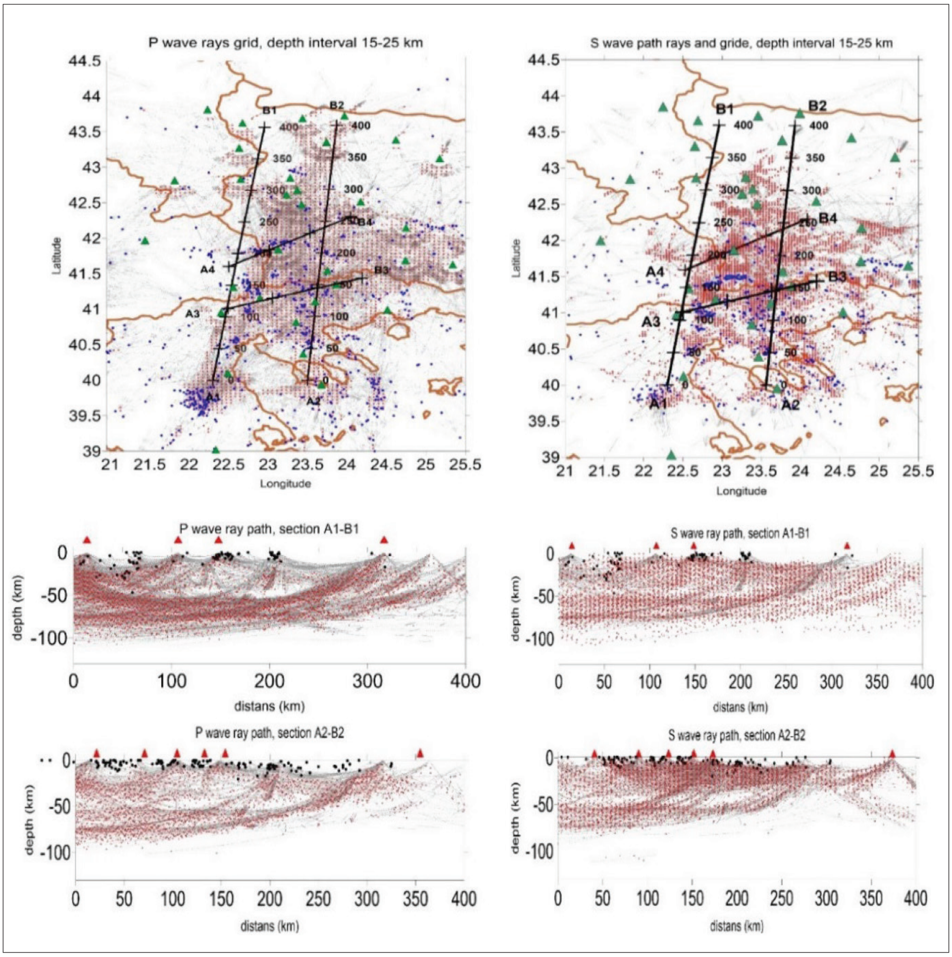

Fig. 3. Profiles A1-B1 and A2-B2 with distances [in km] for the P- and S-waves – left; and rays from the sources to the seismic stations (triangles) in depth – right.

1D model optimization

The data processing starts with the determination of a preliminary source location and the optimization of the one-dimensional velocity model (Figure 4 a). To assess

- The robustness of this procedure, we ran a series of tests (Figure 4 b) with the real observations data.
- The 1D model that best approximate the observed data was determined by testing different initial velocity models. Each of the five models tested was based on earlier literature information
- The RMS residuals after 1D optimization for all velocity models tested are shown in Table 1. Analysing the P and S residuals, it is concluded that the most probable 1D distribution for the western and south-western region corresponds to model 5 presented in Table 1.

Table 1. RMS values for P and S wave residuals after the first and fifth iteration for different starting Models

Values of RMS of P and S residuals in 1st and 5th iterations for different starting models				
Model	**RMS of P and S residuals, 1st iteration**		**RMS of P and S residuals, 5th iteration**	
	P wave	**S wave**	**P wave**	**S wave**
Model 1	0.678036	0.900532	0.504163	0.843715
Model 2	0.62186	1.08115	0.486333	0.751208
Model 3	0.503481	1.570825	0.479569	0.743028
Model 4	0.457719	1.668452	0.544237	0.741775
Model 5	0.497578	1.708503	0.472819	0.734828

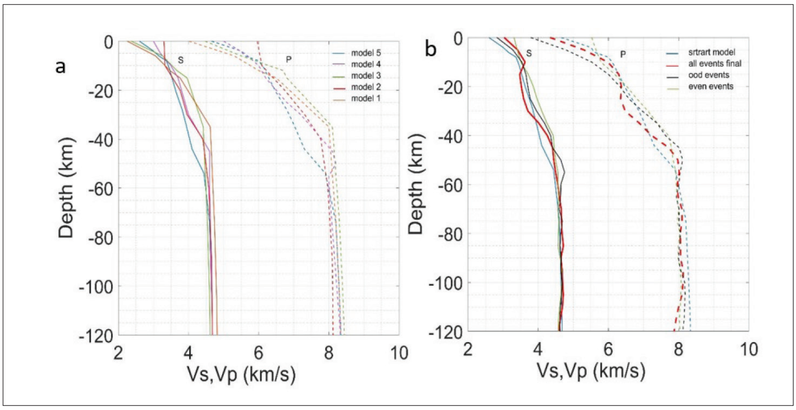

Fig. 4. Optimization of the 1D model for observed data. a) Optimization results with observed data and different starting 1D models. Different colours indicate different models. b) Optimization results for halved data subsets in the odd/even test

Table 2. Vp and Vs in the start and reference 1D model 5 after optimization in the table 2.

Depth (km)	Vp start model 5 (km/s)	Vp (km/s)	Vs start model 5 (km/s)	Vs (km/s)
1		4.63		3.09
5		5.29		3.41
10	5.96	5.84	3.30	3.56
15		6.16		3.65
20	6.09	6.54	3.33	3.83
25		6.85		3.92
30	6.74	7.14	3.76	4.1
35		7.27		4.21
40	7.31	7.58	3.96	4.33
45		8.04		4.52
50		8.07		4.57
55		7.86		4.54
60	7.77	7.92	4.41	4.59
65		7.97		4.69
70		7.97		4.67
75		7.99		4.69
80	7.97	8.02	4.58	4.68

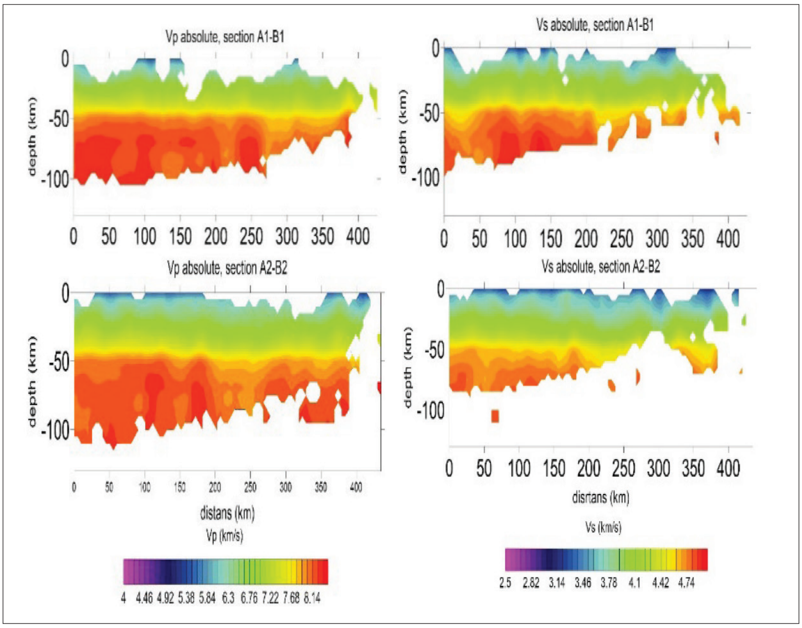

Fig. 5. Vp and Vs absolute values on the cross sections after the optimization.

Results

2D horizontal slices sections have been constructed for depths of 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 km where sufficient rays' coverage is provided. The inversion was performed in five iterations, which is a compromise between computation model and the solution quality (reduction of nonlinear effect). In all sections, calculated values of low and high Vp and Vs anomalies can be seen for various depths up to 50 km. The positive and negative anomalies between the initial and final velocity models vary with ±7%. Findings from different layers reveal that the velocity models show significant low velocity anomalies to the lower crust, larger than expected. Vp/Vs ratio range from 1.6 to 1.9. Horizontal slices are presented in Fig. 6, showing Vp and Vs disturbances in well resolved areas.

The important tectonic structures in the area are marked (red lines) on Fig. 7. The figures also show the location of the sources for each depth. In general, low velocities in the shallow layers can be attributed to severe fracturing, fluid-filled formation in the rock matrix, and weak materials (Serrano et al., 2002).

Low velocity anomalies are also an expression of thermal conductivity, the presence of high fluid flux, and weakened (attenuated) fragments consistent with uplifts from the asthenosphere material to shallow depths because of ongoing lithospheric extension (Dolmaz et al., 2005; Salk et al., 2005; Tarcan et al., 2009; Delph et al., 2015)

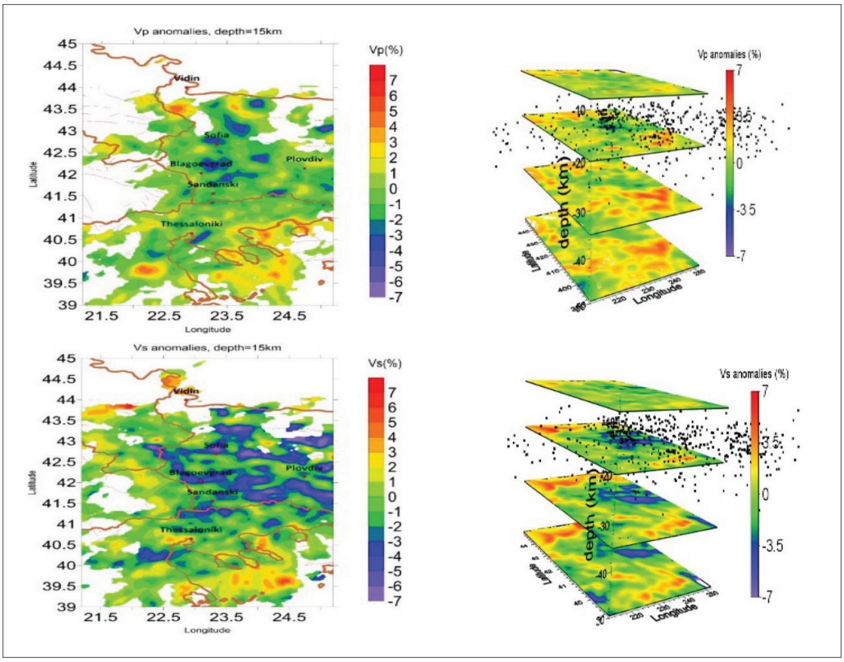

Fig. 6. The Vp and Vs anomalies of the 1D model at 15 km (left) and Horizontal slicing of 5, 20, 35 and 50 km (right).

Discussion

In search of correlation between the anomalies of Vp, Vs, Vp/Vs with other indicators for the geodynamic features of the region several comparative experiments have been done:

- Search of correlation between Vs at different levels and the outlined tectonic units defined by Dabovsky (Dabovsky et al., 2002). The visual correlation (fig. 7) is noticed on the maps presented on fig 7. The gradient areas of low Vs at 15 km depth, coincide with the tectonics unit boundaries outlined in west Bulgaria especially Srednogorie, Rila-Rhodops and Balkans. Such correlation might be explained by the consideration that this upper part of the Earth's crust delineates the depths of destruction of the earth crust due to earthquake stress emission, water and other fluids saturation and in general the weakening effects ofthe different 1991; such as temperature and pressure changes, etc. (Selverstone et al. Evans and Chester 1995; Sanders et al. 1995 г.; Faulkner et al. 2010) geodynamic processes
- The visual correlation between Vp/Vs ratio at the depth of 20km with the gravity Bouguer vertical gradient (P. Trifonova et all, 2013) is another indicator about the relationships between these two parameters. Possible geophysical interpretation could be in a search of the penetration of deep faults in the coinciding areas – fig. 8

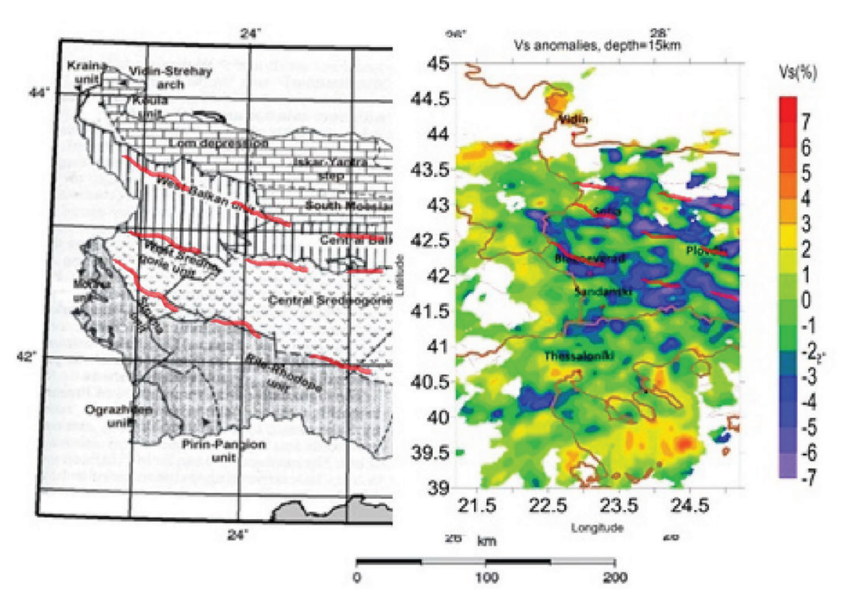

Fig. 7. Tectonic scheme of Bulgaria (modified from Dabovsky et al., 2002) and the Vs anomalies at depth 15 km (right).

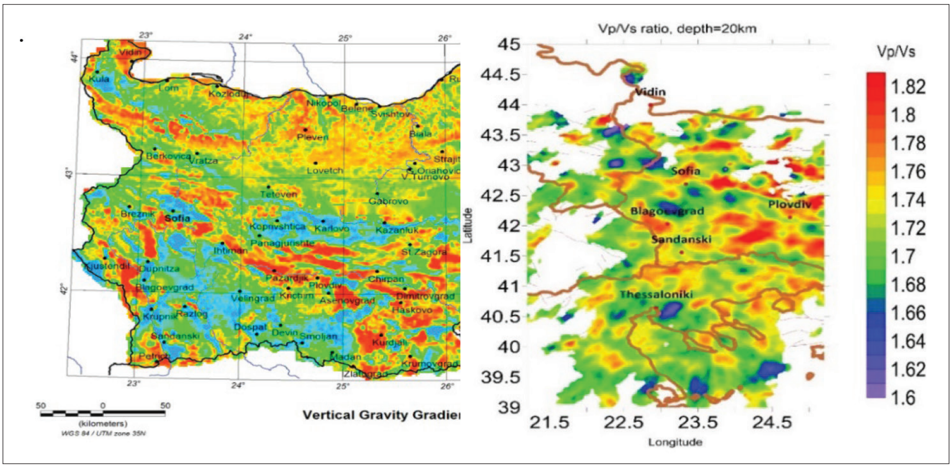

Fig. 8. Map of the vertical gravity gradient (VGG) of Bouguer gravity anomalous field in Bulgaria. The positive (red) and accompanying negative (blue) gradients represent single gradient anomaly

Accuracy tests

To control the accuracy of the calculations – an experimental test was performed. Two calculations have been done with the "odd" events and with the "even" events. The odd and the even events are according the numbering in the initial data set. The results are presented on fig. 9. for both cross-sections.The accuracy varied between 6% (A1-B1) and 11 % (A2-B2).

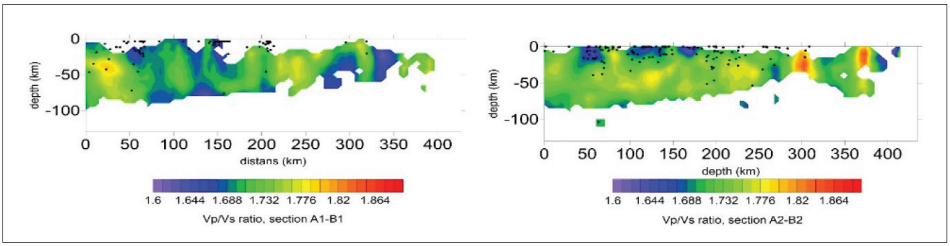

Fig. 9. Vp/Vs ratios on the cross section A1-B1 (left) and A2-B2 (right).

The test results with "even and odd" events in a horizontal plane at a depth of 5 km are shown in Fig. 10. It can be seen that all major anomalies are identified quite reliably in both models, thus presenting their reliability. The remaining smaller anomalies where differences are observed are most likely a result of a random factor and should not be taken into account in the interpretation. Another spatial synthetic checkerboard test was used to evaluate the spatial resolution of the model.

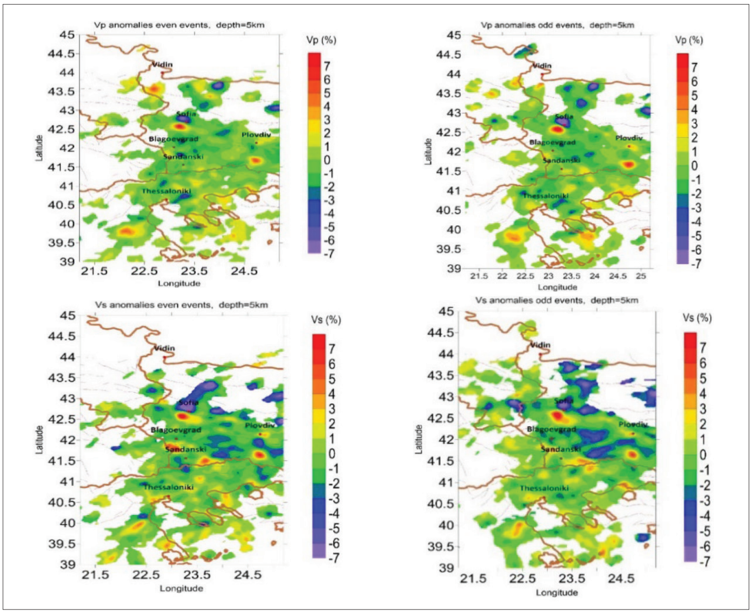

Fig. 10. Vp and Vs anomalies for the odd and the even events at depth 5 km

In this test, a synthetic model alternated rectangular positive and negative anomalies with a lateral size of 30 × 30 km. This model used the real data inversion. In order to obtain the best values of the inversion parameters, several tests were conducted with the synthetics. The result of the test is that the recovery of the cells of the "Chess board" is reliable and shows that the spatial resolution is rather good (fig. 11).

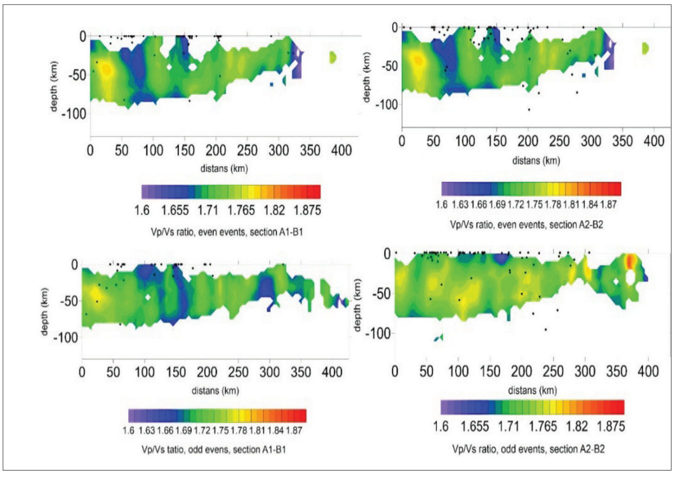

Fig. 11. Cross-sections and visual anomalies of Vp/Vs ratios for odd and even numbered seismic events

Conclusions

The methodology and results about a seismic tomography of the SW Bulgaria and surroundings are presented. The results show a very complex structure in both – lateral and depth directions with variations of about +/- 7 % deviations around the optimized velocity model obtained by a huge amount of initial data. From the recent geodynamics point of view this means that the complicated block structures are dominated by lateral and depth variations of the velocities and the ratio Vp/Vs.

Several parameters are compared by visual correlations of Vp, Vs, Vp/Vs at different depths with other elements of natural geophysical fields and tectonic implications. Future interpretations are intended to correlate the deep earth's structure with seismicity and other geophysical parameters.

The performed tests about the accuracy of the obtained results, the spatial distribution of calculation cells is investigated by two methods – odd and even seismic events as sources of the rays for inversion and the ”chess table” cross-correlation for the spatial resolution optimization. The results about the accuracy confirmed deviations in the range of 6-11% in comparative mode.

Acknowledgment. Authors acknowledge the reviewer D. Solakov for the fruitful discussion and recommendations improving the quality of the presented paper.

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P. Trifonova et all, Regional pattern of the earth’s crust dislocations on the territory of Bulgaria inferred from gravity data and its recognition in the spatial distribution of seismicity, 2013

Модел за сеизмична томография на земната кора на югозападна България и околните райони

Е. Ойнаков, И. Александрова, М. Попова. Б. Рангелов

Резюме: Статията се занимава с томографични изследвания на нееднородностите в кората на Земята в югозападния район на България и техните геодинамични особености. Основната цел е да се разкрият връзките между модела на сеизмичната томография и структурите на корните нееднородности, разположени в югозападната част на България и околните райони. Тази цел е тясно свързана със сеизмичната активност в региона, където се случват силни земетресения в Кресна-Крупник (M7.2 и M7.8, 1904), Валандово (M6.7, 1931) и Скопие (M6.1, 1963) с множество разрушения и жертви. Има и други по-малко активни сеизмични източници като Велинград, Места, Струма и други с по-нисък сеизмичен потенциал. Сеизмичният модел на томографията, който изчислява остатъците на скорост за P и S сеизмични вълни от оптималния модел на скорост, помогна да се установят възможните причини за геодинамичните особености на региона. Откритите скоростни аномалии кореспондират доста добре с предишно изследвани геофизични аномалии (промени в дълбочината на скоростите, градиенти на астеносферата, топлинна проводимост, наситеност с течности и др.) и геодинамични особености (фрактури, фолти, грабени и хорсти, корстни движения и др.). Локалната сеизмичност също е взета предвид, като показва по-голяма концентрация на епицентъра в близост до установените области с градиент на скоростта. Извършените тестове относно точността на изчисленията и текущата интерпретация помогнаха за повишаване на надеждността на получените резултати.

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ОЦЕНКА НА ПАРАМЕТРИТЕ НА АФТЪРШОКОВ СЕИЗМИЧЕН РЕЖИМ НА ЗЕМЕТРЕСЕНИЯ С МАГНИТУД Mw>6 В ПРОСТРАНСТВЕН ПРОЗОРЕЦ 18° – 30° E/ 34° – 42° N

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Абстракт. Афтършоковата активност е израз на вискозоеластична релаксация на напреженията в средата, натрупани като резултат от процесите на разрушение в огнищната зона на главното земетресение. Изследване на разпределението на вторичните събития е от съществено значение за разбиране физиката на сеизмогенезиса. В настоящото изследване е представено поведението във времето и пространството на вторични трусове след осем земетресения в периода 1995-2020 г. с магнитуд $M_W > 5.9$ в пространствен прозорец 18° –30° E/ 34°–42°N. Приложени са модифицираният закон на Omori и законът на Gutenberg- Richter. Определен е параметърът, характеризиращ затихването на афтършоковата активност -p, както и константите c и K използвайки ZMAP в среда MatLab. Тези параметри са полезни за оценка поведението на вторичните трусове във времето. Скоростта на затихване на вторичните събития дава представа за процесите на освобождаване на напреженията след основното земетресение. В резултат на анализа е показано, че параметрите на серия вторични трусове зависят, както от магнитуда, така и от сеизмотектонската обстановка и състоянието на околната среда.

Ключови думи: силни земетресения, каталог, параметри на затихване

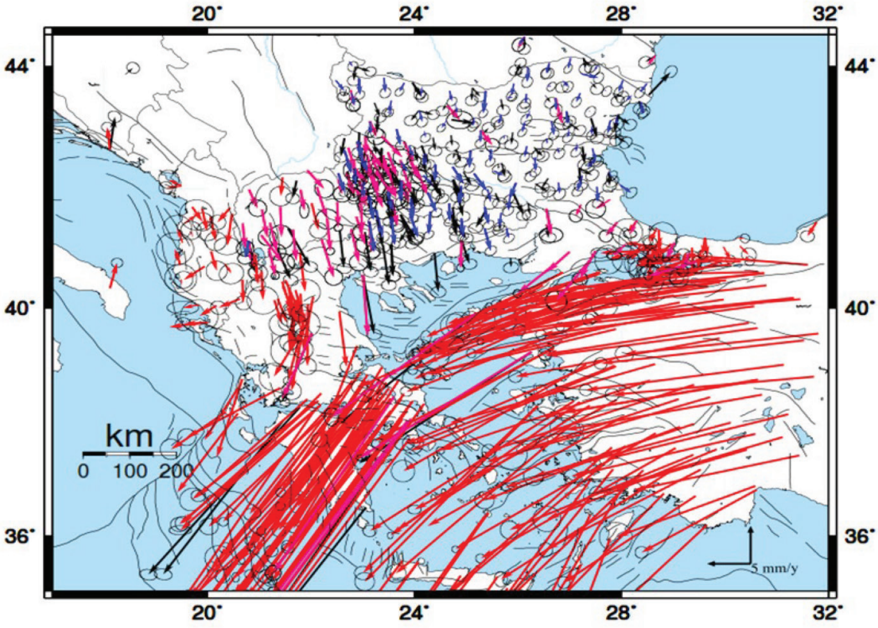
Въведение

Афтършоковата активност е поредица от събития, възникването на които се наблюдава, когато от околната среда се освобождава натрупаната във времето енергия, и продължава до момента, в който броят на събитията за единица време е равен на дългосрочния сеизмичен фон. Въпреки че, понякога се наблюдава статистическа променливост в количествените показатели на вторичния земетръсен процес, тяхното описание удовлетворява три емпирични зависимости с разумно добро приближение: закона за повторяемостта на Гутенберг-Рихтер (Gutenberg, Richter, 1944), законът на Bath (Bath M., 1965), който предполага, че разликата в магнитуда между главния трус и „най-големия" очакван вторичен трус е постоянна. За разлика от повечето от физичните процеси в природата, които затихват експоненциално във времето, афтършоковият процес затихва по обратен степенен закон – феноменална негова характеристика, представена чрез третият закон - закона на Омори (Omori, F., 1894b), стандартната форма на модифицирания закон на Omori, направена от Utsu (Utsu T., 1962). Спадът в активността започва по-късно, колкото по-високо е нивото на напрежение в земната кора.

В настоящата статия е изследвано пространствено-времевото разпределение на последователностите от вторични трусове на осем земетресения в периода 1995-2020 г. с магнитуд по сеизмичен момент $M_W \geq 5.9$ в пространствен прозорец 18–30 E/ 34–42 N. Изследване на пространствено-времевото разпределение на сеизмичността на територията на Балканите и връзката с параметрите на други геофизични полета е представено в статиите на (Oynakov et all 2020; Raykova et all,2019; Chamati, 2023).

Изследваните земетресенията попадат в една от най-динамичната част от Алпо–Хималайският сеизмичен пояс. Тектониката на Средиземно море, в конвергентния граничен регион между Африка и Евразия, е сложна и включва движенията на множество микроплочи и структури от регионален мащаб. Анализът на полето на получените съвременни движения и напрежения на земната кора се разглежда в контекста на активните тектонски процеси, протичащи в района на Източното Средиземноморие. Информацията за съвременните движения на земната кора е от важно значение за верификация на хипотезите за съвременните геодинамични процеси, протичащи в България и на Балканския полуостров (Solakov et.al, 2019). На фигурата се очертават двете ротационни движения в района на Източното Средиземноморие – обратно на часовниковата стрелка на Анадолската и Егейската микроплоча, и по посока на часовниковата стрелка на територията на Източна Албания, Македония и Западна България с увеличаващи се по абсолютна стойност скорости в посока север-юг и северозапад.

Потвърждава се наличието на транзитна зона между Евроазитската континентална плоча и Егейската микроплоча на територията на България – Южнобалкански екстезионен район с преобладаваща екстензия с посока С-Ю. Хоризонталните скорости южно от паралела 43° нарастват на юг, от ~1.5-2 mm/y в района на Софийския грабен до ~10-11 mm/y в Северноегейския регион и достигат ~30 mm/y при Коринтския залив (Solakov et. al., 2019). Полето на хоризонталните скорости показва, че Западните Балкани, включително Албанидите, са подложени на ротация по посока на часовниковата стрелка около полюс в Северна Албания (Скутари). Източна Алабния, Македония и Западна България са обект на значителни деформации – от ектензия E-W в Източна Албания до екстензия N-S в Македония, Западна България и Северна Гърция (Solakov et. al., 2019). Цялата област има значително, увеличаващо се на юг движение спрямо Евразия (Solakov et. al., 2019).

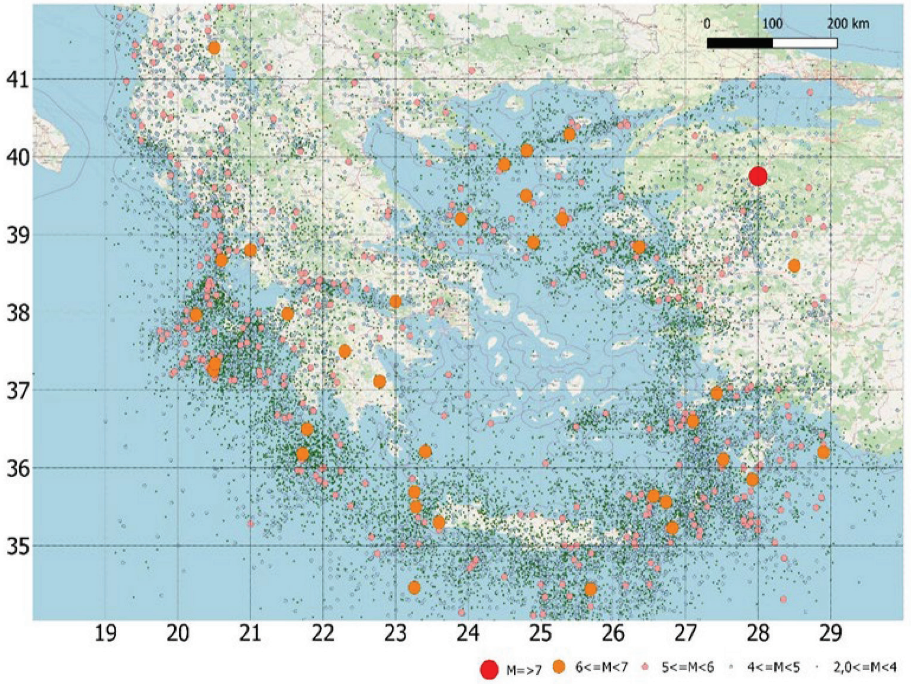


Фиг. 1. Съвременните геодинамични процеси (Solakov et al., 2019)

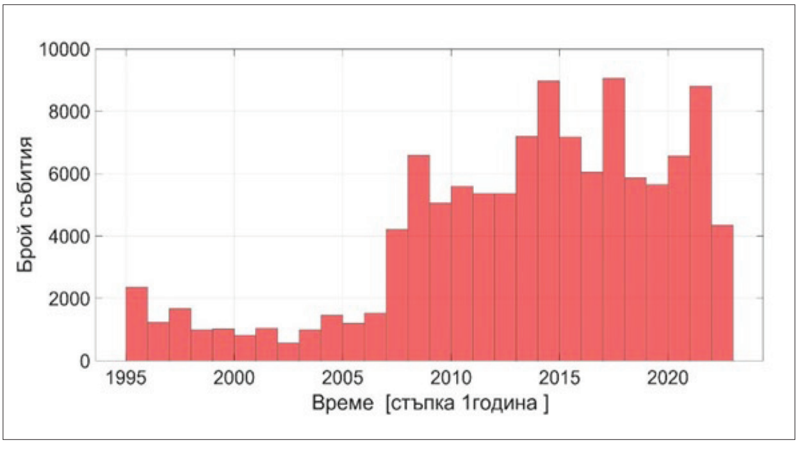
Данни

В изследването е използван регионалният каталог на земетресенията на Атинския Университет (University of Athens- http://www.geophysics.geol.uoa.gr) за периода 1905.01.01 - 2009.12.31 (Makropoulos, et al., 2012), добавени са събития от 2010 до 2022 г. от същия източник , както и непрекъснато обновяващ се каталог за период 1905-2022.12.31 г., на Turkish Bogazici University KOERI (http://www.koeri.boun.edu.tr/sismo/2/earthquake-catalog/). Взривове и дублиращите се събития са разпознати и отстранени алгоритмично с използване на софтуерния пакет – ZMAP, и по-късно проверени чрез визуална оценка. Афтършоковите последователности са идентифицирани чрез алгоритъма на Gardner, J. K. и L. Knopoff (1974). В резултат за изследвания период извадката от събития се състои от 116 739 земетресения с магнитуд в интервала $2.0 \leq M_W < 7.0$ (фиг. 2) и с дълбочини $1.0 \leq h \leq 252$ km.

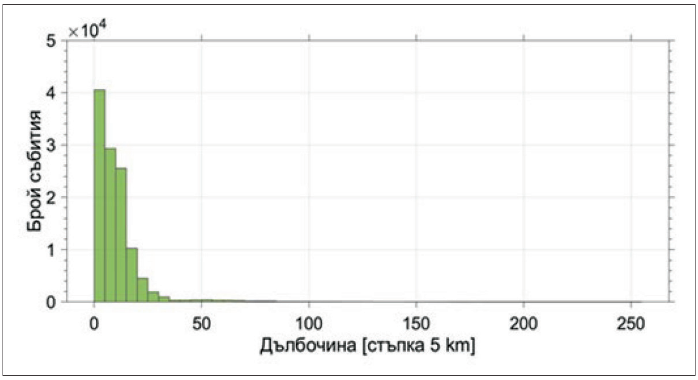
Количественото описание на сеизмичният режим включва сравнителен анализ на сеизмичността в различни райони и различни времеви интервали. На фигури (3-5) са представени някои от статистическите характеристики на каталога: събитията са неравномерно разпределени във времето (фиг. 3); хипоцентрите на близо 90% от събития са разположени на дълбочина 1–20 km (фиг. 4); основната част от каталога се състои от слаби събития с M_W = 2.0-3.5 (фиг. 5).



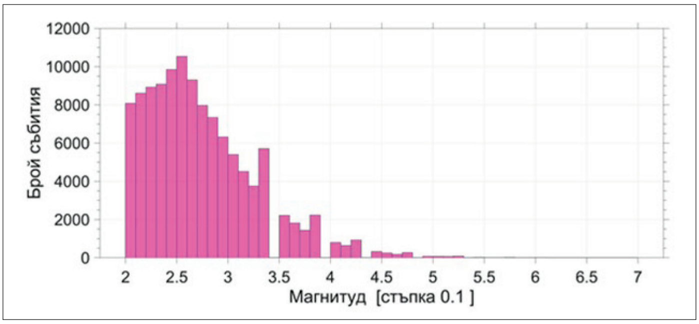
Фиг. 2. Разпределение на епицентрите на земетресенията реализирани в пространствен прозорец 18°–30° E/ 34°–42° N. за периода 1905-2022 г.



Фиг. 3. Времево разпределение на земетресенията реализирани за периода 1995-2022 г. в пространствен прозорец 18°–30° E/ 34°–42° N.



Фиг. 4. Дълбочинно-честотно разпределение на земетресенията.



Фиг. 5. Брой събития спрямо магнитудна оценка.

Метод

Разпознаване на едно земетресение като афтършок или главно събитие е възможно само след реализацията на цяла земетръсна серия. За идентифициране на вторичните трусове реализирани във времето след основно събитие в това изследване, се използват критериите дефинирани от Gardner, J. K. and L. Knopoff (1974). Съгласно тази дефиниция ако се разгледат две събития от подредена във времето серия земетресения с индекси „*m*“ и „*a*“ и магнитуди, съответно M_m и M_a, то второто ще бъде афтършок на първото ако са изпълнени следните условия:

$$\begin{aligned} &M_a < M_m \\ &0 < t_a - t_m < T(M_m) \\ &0 \le R_{am} < R(M_m), \end{aligned} \tag{1}$$

където t е време на възникване, R_{am} е разстоянието между хипоцентрите (епицентрите) на главното събитие и съответния афтършок, а $T(M_m)$ и $R(M_m)$ са емпирични функции на магнитуда на главното земетресение. Граничните стойности на тези функции, съответно T_a (M_m) и $R_a(M_m)$, са определени по модификация на функционалните зависимости на Gardner, J. K. and L. Knopoff (1974), получена за централни Балкани от Христосков, Лазаров (1981). Изследванията на Христосков и Лазаров (1981) показват, че размерите на пространствено-времевите области на афтършоковите поредици в средната част на Балкански полуостров значително превишават граничните измерения, определени от Gardner, J. K. and L. Knopoff (1974). Предложената от авторите модификация съответства на сеизмо-тектонските условия, определящи сеизмичния процес в централни Балкани. В настоящото изследване за дефиниране границите на афтършоковите серии в пространството и времето, като първо приближение, са приложени следните уравнения (съгласно Христосков, Лазаров, 1981):

$$\begin{aligned}
&\log R_a(M_m) = 0.9696 + 0.1243\, M_m \\
&\log T_a(M_m) = -0.62 + 0.56\, M_m \qquad (M_m < 6.0) \\
&\log T_a(M_m) = -5.25 + 2.15\, M_m - 0.137\, M_m^2 \qquad (M_m \geq 6.0),
\end{aligned} \tag{2}$$

където R_a е максималният размер на афтършоковата област, а T_a е предполагаемата продължителност на поредицата във времето.

За оценка на параметрите на разпределенията на афтършоковите събития във времето е използван програмен пакет Zmap в среда MatLab. Много изследователи са анализирали различни каталози на земетресения с помощта на този софтуер (Wiemer 2001; Oynakov, et al, 2020).

За всяко събитие са изчислени параметрите p, c, K от модифицираната формула на Omori (Utsu, 1961, 1969):

$$n(t) = K(t + c)^{-p}\,, \tag{3}$$

където p е параметър характеризиращ затихването на афтършоковата активност във времето; $n(t)$ честота на събитията за единица време t; K и с константи, а b стойността от релацията на Гутенберг-Рихтер.

За формална идентификация на афтършоковете също е използван закона на Bath., съгласно който, разликите в магнитудите ΔМ между основното събитие M_{ms} и неговия най-силен афтършок с магнитуд $M_{as\text{-}max}$:

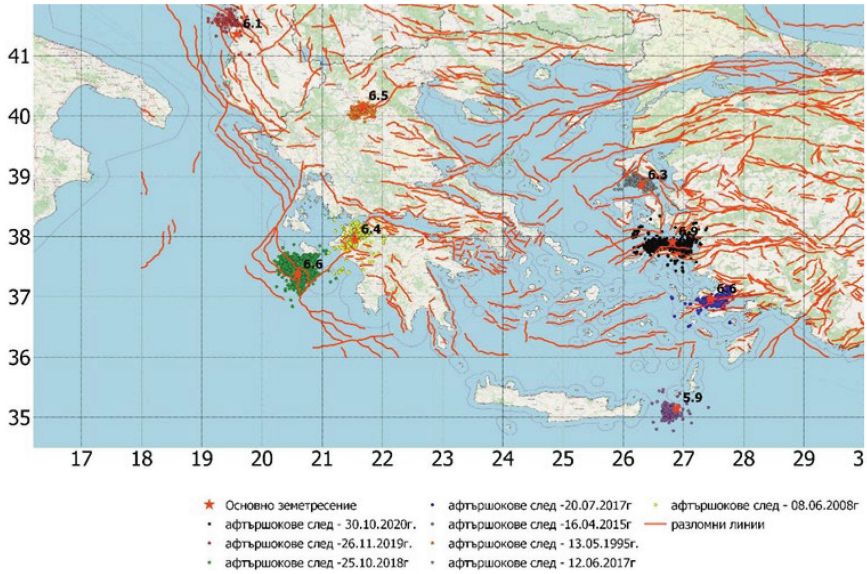
$$\Delta M = M_{ms} - M_{as\text{-}max}, \tag{4}$$

е константа ΔМ=1,16±0,46 (Shcherbakov R., Turcotte D. L., 2004).

Резултати

Пространственото разпределение на епицентрите на основните земетресения и определените за тях афтършокови поредици е представено на фиг. 6. Изобразените на картата активни разломи в разглежданата територия са по данни от GEM

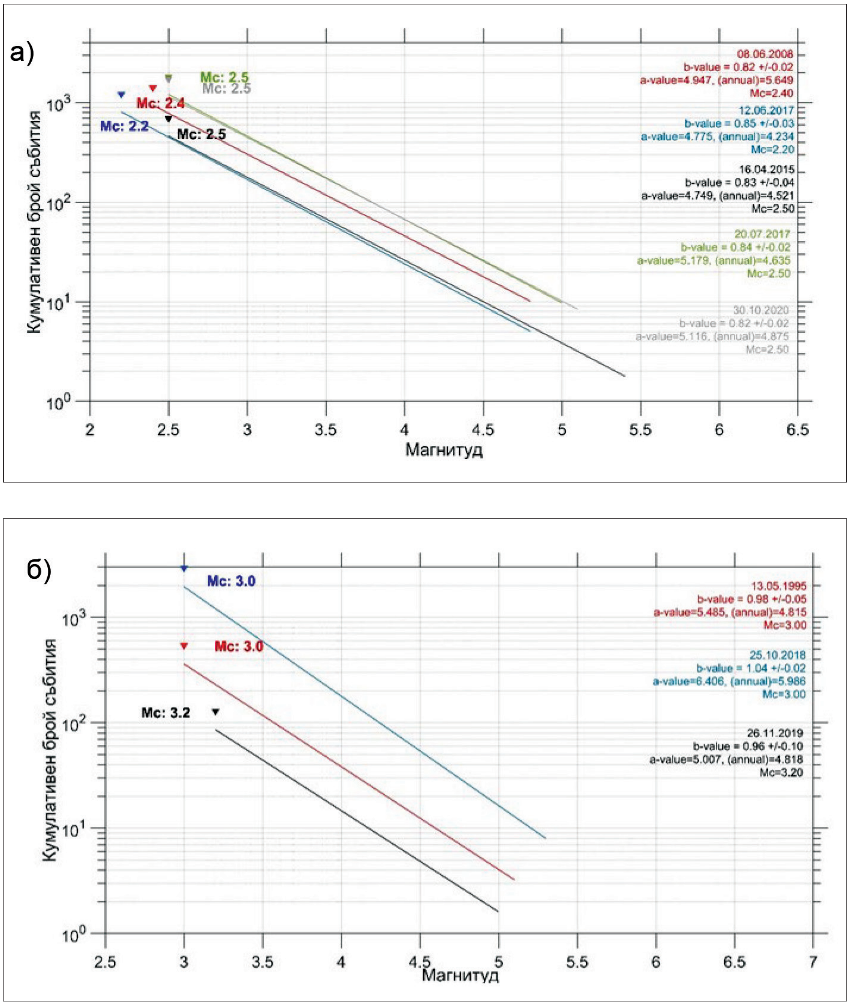
Global Active Faults (https://github.com/GEMScienceTools/gem-global-active-faults). Според пространственото разпределение на епицентрите на събитията може да разделим 8-те основни групи от земетресения на две групи: 1-ва група - епицентрите на афтършоковите събития са разположени в определено направление от епицентъра на основното събитие (26.11.2019-SW; 13.05.1995-S; 16.04.2015-SW; 20.07.2017-NE) и 2-ра група с приблизително елипсовидно и концентрично пространствено разпределение.



Фиг. 6. Пространствено разпределение на епицентрите на основните и афтършокови събития.

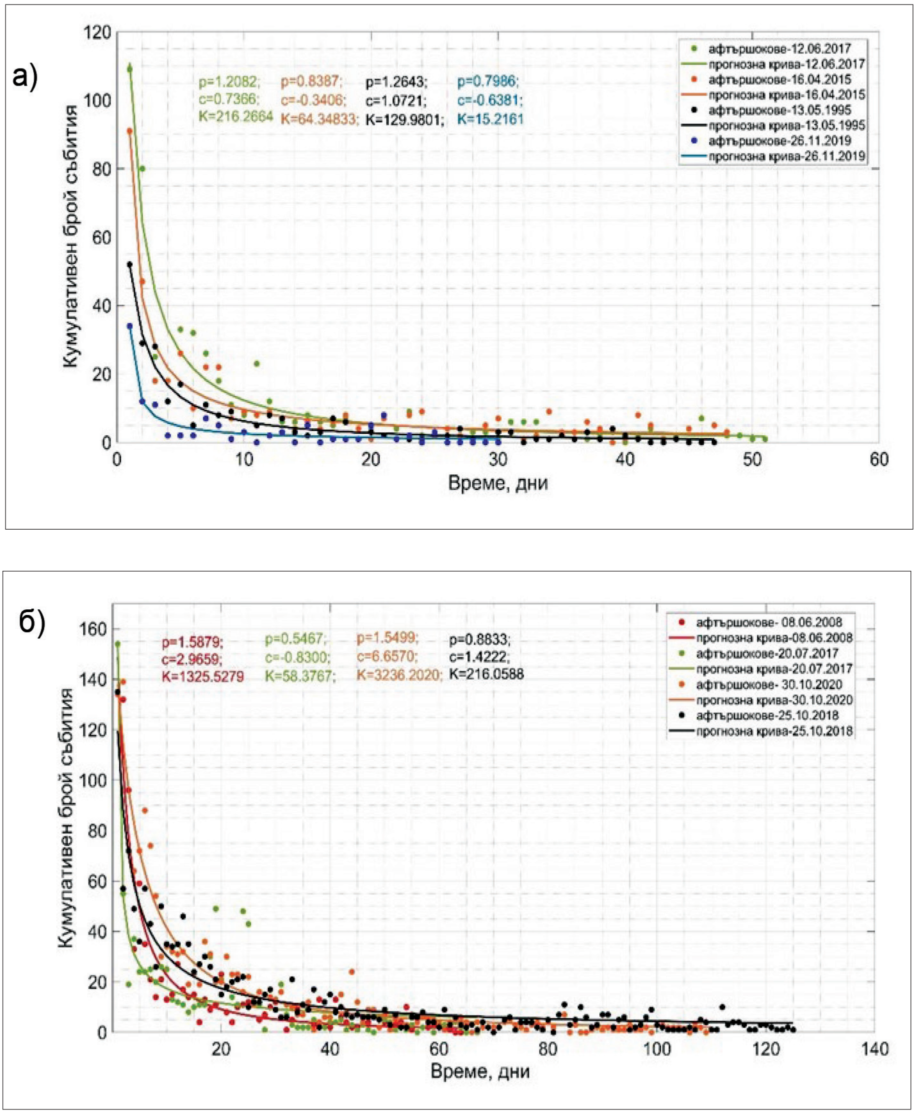
За всяко земетресение са оценени отделно параметрите характеризиращи афтършоковия процес, продължителността на афтъшоковата поредица, разликата в магнитудите на основния трус и най-силния вторичен трус, както и общия брой идентифицирани вторични трусове. Анализът на получените данни показа, че различните основни земетресения се проявяват по напълно различни начини в своята вторична (афтършокова) активност.

Фигура 7 представя магнитудно - честотно разпределение, за определяне пълнотата на събитията, разположени в избраната област на различните поредици. Разпределението показва, че компилираният набор от данни за 5 от поредиците е непълен под Mc=2.2 (фиг. 7а), за останалите 3 земетресения праговият магнитуд е Mc=3.0 (фиг. 7б). Стойностите на параметрите a и b от закона на Гутенберг-Рихтер за различните серии варират от $4.749 \leq a \leq 6.406$ и съответно за параметъра b стойностите варират в интервала $0.82 \leq b \leq 0.85$ за 5 от събитията (фиг. 7а) и в диапазона $0.96 \leq b \leq 1.04$ за три от земетресенията с по -висок магнитуден праг (фиг. 7 б).



Фиг. 7. Магнитудно-честотно разпределение на изследваните афтършокови серии след земетресенията на: а) 08.06.2008, 12.06.2017, 16.04.2015, 20.07.2017, 30.10.2020 б) на 13.05.1995, 25.10.2018, 26.11.2019.

Стойностите на параметрите на модифицираната формула на Omori p, c и K са предствени в таблица 1 и на фигура 8. Стоиностите на параметрите се променят в интервалите: $0.55 \leq p \leq 1.59$, $0,83 \leq c \leq 6,66$, за $58,38 \leq K \leq 3236,2$ за земетресенията от фиг. 8 а) и $0.8 \leq p \leq 1.26$, $0.34 \leq c \leq 1.07$, $15.2 \leq K \leq 216.3$, за земетресенията от фиг. 8 б). Може да се направи заключение, че за поредиците предствени на фиг. 8 б), стойности на параметрите от модифицираната формула на Омори съответстват на получените от други автори (Utsu et al., 1995; Kagan, 1987, 2004).



Фиг. 8. Зависимост на кумулативния брой вторични събития и изчислените *p, c,* и *K* - стойности след земетресенията: а) на 08.06.2008, 20.07.2017, 30.10.2020, 25.10.2018 б) на 12.06.2017, 16.04.2015, 13.05.1995, 26.11.2019.

Получените стойности за константата Δ*M* от закона на Bath (табл. 1) варират в диапазона $0.8 \leq \Delta M \leq 1,6$ което съответства на получената от (Shcherbakov R., Turcotte D. L., 2004) стойност $\Delta M=1,16\pm0,46$.

Табл. 1. Оценки на параметрите K, p, c, b -стойностите и ΔM (закона на Bath) за различните поредици.

Data, time	Mw	Lat./Long. degree	Depth, km	b	Number of events	p	c	k	ΔM, Bath law
13.05.1995 08:47	6.5	21.70/40.15	12	0.98	257	1.26	1.07	129.9	1.1
08.06.2008 12:25	6.4	21.52/37.97	20	0.82	944	1.59	2.97	1325.5	1.5
16.04.2015 18:07	5.9	26.80/35.23	20	0.83	427	0.84	0.34	64.35	0.8
12.06.2017 12:28	6.3	26.37/38.86	13	0.85	530	1.21	0.74	216.27	1.5
20.07.2017 22:31	6.6	27.44/36.99	11	0.84	878	0.6	0.83	58.38	1.2
25.10.2018 22:54	6.6	20.50/37.36	20	1.04	1459	0.88	1.42	216.1	1.2
26.11.2019 02:54	6.1	19.58/41.36	7	0.96	111	0.80	0.64	15.21	1.2
30.10.2020 11:51	6.9	26.80/37.92	13	0.82	1543	1.55	6.66	3236	1.6

Заключение

В заключение от анализ на получените резултати за осемте земетресения в рамките на избрания пространствен прозорец обхващащ времевия период от 1995 г. до 2022 г., може да се отбележи че:

- пространствената картина на афтършоковата активност показва, че главното земетресение и последвалите го афтършокови събития се групират по разломни структури и при разгледаните 8 поредици се обособяват две групи: 1-ва група - епицентрите на афтършоковите събития са разположени в определено направление от епицентъра на основното събитие (26.11.2019-SW; 13.05.1995-S; 16.04.2015-SW; 20.07.2017-NE) и 2-ра група с приблизително елипсовидно и концентрично пространствено разпределение
- чрез моделиране на афтършоковия процес във времето се оформя следната картина включваща информация за промяната на параметрите от закона на Omori, които са в интервалите: $0.6 \le p \le 1.59$ и $0.34 \le c \le 6{,}66$. Като за поредиците след земетресенията - на 12.06.2017, 16.04.2015, 13.05.1995, 26.11.2019 стойности на параметрите от модифицираната формула на Омори съответстват на получените от други автори (Utsu et al., 1995; Kagan, 1987, 2004).

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Assessment of Aftershock Seismic Regime Parameters for Earthquakes with Magnitude Mw > 6 in the Spatial Window 18°–30° E / 34°–42° N

M. Popova

Abstract. Aftershock activity reflects the viscoelastic relaxation of stress in the Earth's crust, which accumulates as a result of the rupture processes within the focal zone of the main earthquake. The study of the distribution of secondary events is crucial for understanding the physics of seismogenesis. This research presents the temporal and spatial behavior of aftershocks following eight earthquakes between 1995 and 2020 with magnitudes Mw > 5.9 in the spatial window 18°–30° E / 34°–42° N. The modified Omori law and the Gutenberg-Richter law are applied. Parameters characterizing the decay of aftershock activity, such as the parameter p and constants c and K, are determined using ZMAP in the MATLAB environment. These parameters are valuable for assessing the temporal behavior of aftershocks. The decay rate of aftershock events provides insights into the stress release processes following the main earthquake. The analysis demonstrates that the parameters of aftershock sequences depend on both the magnitude of the main event and the seismotectonic environment, as well as the conditions of the surrounding medium.

Keywords: strong earthquakes, catalog, decay parameters

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Времево разпределение на афтършокова поредица след земетресението от февруари 2018 г. реализирано в района на град Асеновград, сеизмогенна зона Марица

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Абстракт: Статистическият анализ се прилага за изучаване времевия модел на афтършоковата активност наблюдавана след земетресението от 21 февруари 2018 г. с магнитуд по сеизмичен момент M_W4.7, реализирано в района на град Асеновград, сеизмогенна зона Марица. Въз основа на предположението, че вторичните трусове са разпределени във времето като нестационарен Поасонов процес се използва модифицираната формула на Омори за оценка на параметрите (K, c и p). Трансформацията на времета скала t в честота-линеализирана скала τ се прилага за определяне на най- добрата връзка между афтършоковата активност и различни статистически модели. Затихването на афтършоковата активност се описва добре с модифицираната формула на Омори и е установена мултиполна активност с две вторични серии.

Ключови думи: земетресение, времево разпределение, афтършок, сеизмогенна зона Марица

Въведение

Земетресението като природно явление се определя от голямо брой фактори, които трудно се контролират и не могат да бъдат непосредствено наблюдавани. Земетресението е явление със силно изявен дуализъм. От гледна точка на науката, сеизмичните вълни, породени от земетресенията са изключително полезни за изучаване на вътрешния строеж на Земята, а от социално - икономическа гледна точка това явление може да има катастрофален от характер. Съвкупността от земетресения в дадена област, разглеждана във време, пространство и енергия, определя сеизмичния режим на тази област. Земетресенията са неравномерно разпределени в пространството и времето. Изследването на пространствено-времевото разпределение на земетресенията е съществено за опознаване на сеизмогенния процес.

В глобален аспект, земетресенията са концентрирани по сеизмични пояси, които съвпадат с контактните зони между най-крупните геоструктури - тектонските плочи. Разпределението на земетресенията във времето, в първо приближение, добре се описват с Поасонов процес, ако от сеизмологичните данни се изключат времевите клъстери (групи). Поасоновият процес предполага стационарност (постоянна скорост на реализация) и като модел на сеизмичния процес изключва възможността земетресенията да се генерират във времеви клъстери (групи). Групите от земетресения се разглеждат като съществен не случаен елемент на сеизмичността. Изявени и разпознаваеми клъстери от земетресения са фор-афтършоковите поредици и сеизмичните роеве.

От земетръсните групи афтършоковите събития са едни от най-достъпните за наблюдение и се приема, че тяхната реализация е израз на вискозоеластичната релаксация на напрежения в средата. Предполага се, че тези събития са резултат от процесите на разрушение в огнището на главното земетресение и преразпределяне на напреженията след неговата реализация. Пространствено-времевите и енергетичните особености на афтършоковите поредици са традиционен обект на изследване в сеизмологията. Особеният интерес към афтършоковия процес е продиктуван от неговата специфика и особености. От една страна афтършоковите серии са източник на информация за състоянието, както на физико-механичните свойства на средата в огнищата зона, така и за процесите, протичащи в нея. От друга страна не е възможно създаване на физичен модел за сеизмичния процес без да се отчитат параметрите, характеризиращи пространственото, времевото и енергетичното разпределения на афтършоковите събития като съществена част от този процес (Polat et al., 2002, Bayrak и Öztürk, 2004, Ansari, 2017, Enescu and Ito, 2002; Enescu et al., 2011; Kato and Igarashi, 2012; Toda et al., 1998; Utsu et al., 1995; Wiemer and Katsumata, 1999; Wiemer and Wyss, 2000).

Повечето физични процеси затихват експоненциално във времето, а афтършоковият процес, затихва по обратен степенен закон – феноменална негова характеристика, представена чрез модифицираната формула на Omori (Omori, 1894a, b; Utsu, 1957, 1961, 1969):

$$n(t) = K(t + c)^{-p}, \tag{1}$$

където p, K и c са константи.

Основеният параметър p, характеризиращ затихването на афтършоковата активност във времето, е високо информативен както за механизма на релаксация на напреженията, така и за физико-механичните свойства на средата в дадена сеизмогенна зона (Mikumo and Miyatake, 1979; Dieterich, 1978).

В настоящото изследване е анализирано времевото разпределение на афтършоковата поредица след земетресението от 21 февруари 2018 г. с магнитуд по сеизмичен момент M_W4.7, реализирано в района на град Асеновград, област Пловдив, сеизмогенна зона Марица (T_0=23:41:58, φ=42.07, λ=24.91 и h=14 km).

Сеизмотектоника на района

Средногорският регион обхваща Средногорската зона, голяма част от Сакар-Странджанската зона (Тектонско райониране на територията на България, от Отчет ГФИ 07-02, 2008). Активните разломи са главно със субпаралелно и северозапад-югоизточно направление, разположени по цялата територия на региона. Сеизмичността може да бъде привързана към активните разломи. В този регион, в сеизмогенна зона Марица са реализирани едни от най-силните земетресения на територията на България.

Сеизмогенна зона Марица е разположена в Централна Южна България. Сеизмичността в зоната е привързана към добре известната Маришка разломна система, простираща се в направление ЗСЗ-ИЮИ. Най-силните известни земетресения, станали в зоната, са събитията от 1928 г.: Чирпанското земетресение от 14 април 1928 г. с магнитуд M_W=6.5 и Пловдивското от 18 април 1928 г. с магнитуд M_W=7.1.

Земетресенията предизвикват значителни разрушения в градовете Пловдив, Чирпан и Първомай, както и в много други селища (илюстрирано на Фиг. 1). Двете земетресения са последвани от интензивна афтършокова активност, продължила до края на 1933 г. (Simeonova, Solakov 1999).

След земетръсната серия от 1928 г., в зоната се наблюдава затишие на силните земетресения с $M_W^3$6.5, което продължава и до сегашният момент. През инструменталния период в зоната са наблюдавани основно умерени земетресения с магнитуд между M=4 и M=5. Каквото е и събитието (с магнитуд M_W=4.7), анализирано в настоящото изследване.

Фиг. 1. Разрушения след земетресението от 14 април 1928 г., град Чирпан

Метод и входни данни

Метод

Затихването на афтършоковия процес във времето е по обратен степенен закон, който се представя чрез модифицирана формула на Omori: $n(t) = K(t + c)^{-p}$ (Utsu,1961).

Ogata (1983) предлага използването на метода на максимално правдоподобие (ММП) за оценка на параметрите на модифицираната формула на Omori. За прилагане на ММП се допуска, че развитието на афтършоковата активност във времето е нестационарен Поасонов процес с интензивностна функция l(t;q), q=(K, p, c), определена чрез връзката:

$$\lambda(t;\theta) = \lim_{\Delta t \to 0} \frac{P_{\Delta t}(t)}{\Delta t}, \qquad (2)$$

където $P_{\Delta t}(t)$ е вероятността да се реализира събитие в малък времеви интервал $(t, t+\Delta t)$. Тогава функцията на максимално правдоподобие за афтършокова поредица, реализирана в интервал от време [S, T] в моменти $\{t_1, t_2, \ldots, t_k\}$ ($t_1, t_2, \ldots, t_k$ са времената на поява на афтършоковите събития), се дава чрез уравнението:

$$L\left(t_1, t_2, ..., t_k; \theta\right) = \prod_{i=1}^{k} \lambda\left(t_i; \theta\right) e^{-\int_S^T \lambda(t_i;\theta)dt}. \qquad (3)$$

Оценките по максимално правдоподобие за параметрите (векторът на параметрите) се получават от максимизиране на функцията на максимално правдоподобие. За серия без вторични афтършокови поредици, интензивностна функция се определя чрез модифицираната формула на Omori:

$$\lambda(t;\theta) = K(t+c)^{-p} \qquad (\theta = (K, p, c)). \qquad (4)$$

При поредици с изявена вторична афтършокова активност интензивностната функция се представя чрез уравнението от вида (Ogata, 1983):

$$\lambda(t;\theta) = K(t+c)^{-p} + \sum_{i=1}^{m} H(t-T_i) K_i (t - T_i + c_i)^{-p_i}, \qquad (5)$$

където m е броят на вторичните поредици, $H(t)$ е единична функция на Хевисайд и Ti е началото на i-тата вторична афтършокова поредица и $\theta=(K, p, c, K_1, p_1, c_1, ...K_m, p_m, c_m)$.

При коректен избор на интензивностната функция, т.е. на параметрите , афтършоковият процес се трансформира в стандартен Поасонов процес (λ=1) по честотно - линеаризираната времева ос τ. Честотно - линеаризираното време за афтършокова поредица се дефинира като:

$$\tau = \Lambda\left(t\right) = \int_{S}^{t} \lambda\left(s\right) ds = \int_{S}^{t} \left[K\left(s+c\right)^{-p} + \sum_{i=1}^{m} H\left(t-T_i\right) K_i \left(t-T_i+c_i\right)^{-p} \right] ds \,. \qquad (6)$$

Времевата ос t се използва за установяване на отклонения в сеизмичната активност от теоретичния тренд N(τ)=τ, където N(τ) е кумулативният брой събития до момента . Увеличение на активността, в сравнение с теоретично очакваната се разглежда или като изява на вторична афтършокова активност, или като край на афтършоковата активност.

За сравняване на модели за разпределение на афтършоковата активност във времето е приложен информационния критерии на Akaike, AIC (Akaike, 1974). Това е един от най приложимите критерии за сравнение на различни модели, основаващи се на едни и същи данни. AIC се определя с уравнението:

$$\mathrm{AIC} = (-2)\max \ln(\mathrm{Lh}) + 2n, \qquad (7)$$

където ln е натурален логаритъм, Lh е съответната функция на правдоподобие и n-броят на оценените параметри. Този критерий отчита съответствието между данните от наблюденията и заложения теоретичен модел. Модел с по-малка стойност на AIC се счита за по-добре описващ наблюденията.

Данни

В настоящото изследване за афтършок се приема всяко събитие, реализирано във времето след друго земетресение, което изпълнява критериите за афтършок, дефинирани от Gardner and Knopoff (1974). Съгласно това определение ако се разгледат две събития от подредена във времето серия земетресения с индекси „m” и „a“ и магнитуди, съответно M_m и M_a , то второто ще бъде афтършок на първото ако са изпълнени следните условия:

$$\begin{aligned} &M_a < M_m \\ &0 < t_a - t_m < T(M_m) \qquad (8) \\ &0 \le R_{am} < R(M_m), \end{aligned}$$

където t е време на възникване, R_{am} е разстоянието между хипоцентрите (епицентрите) на главното събитие и съответния афтършок, а $T(M_m)$ и $R(M_m)$ са емпирични функции на магнитуда на основното земетресение. Граничните стойности на тези функции, съответно $T_a(M_m)$ и $R_a(M_m)$, са определени по модификация на функционалните зависимости (8), получена за централни Балкани от Христосков, Лазаров (1981). В настоящото изследване за дефиниране границите на афтършоковите серии в пространството и времето, като първо приближение, са приложени следните уравнения (съгласно Христосков, Лазаров, 1981):

$$\log R_a(M_m) = 0.9696 + 0.1243\, M_m \tag{9}$$

$$\log T_a(M_m) = -0.62 + 0.56\, M_m \qquad (M_m < 6.0) \tag{10}$$

$$\log T_a(M_m) = -5.25 + 2.15\, M_m - 0.137\, M^2_m \quad (M_m \geq 6.0), \tag{11}$$

където R_a е максималният размер на афтършоковата област, а T_a е предполагаемата продължителност на поредицата във времето.

Основен източник на данни за разгледания сеизмичен клъстер са от Националната оперативна телеметрична система за сеизмологична информация (НОТССИ). За оценка параметрите на разпределенията на афтършоковите събития във времето е разработен програмен пакет на PASKAL (представен в Солаков, 2010).

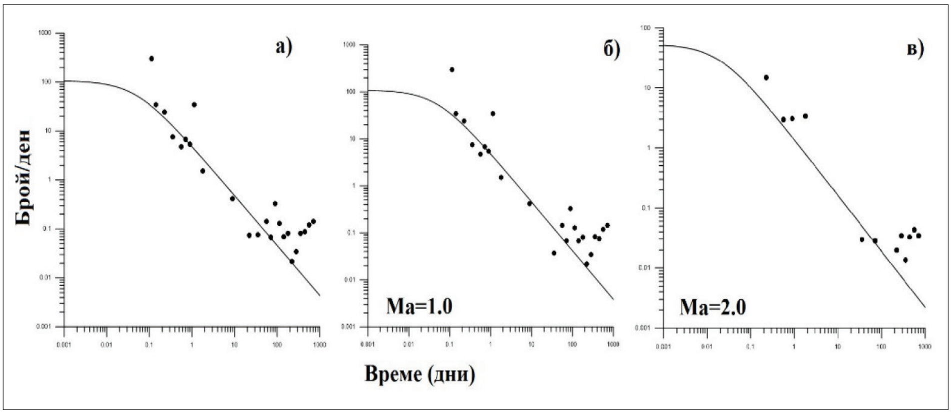
Земетресението от 21.02.2018 г. (M_w4.7) е последвано от изявена афтършокова активност, включваща 99 събития с магнитуд в интервала $1.0 \leq M_p \leq 3.7$, реализирани за 665 дни. От тези събития с магнитуд $M_p \geq 2.0$ са само 28 събития.

Резултати

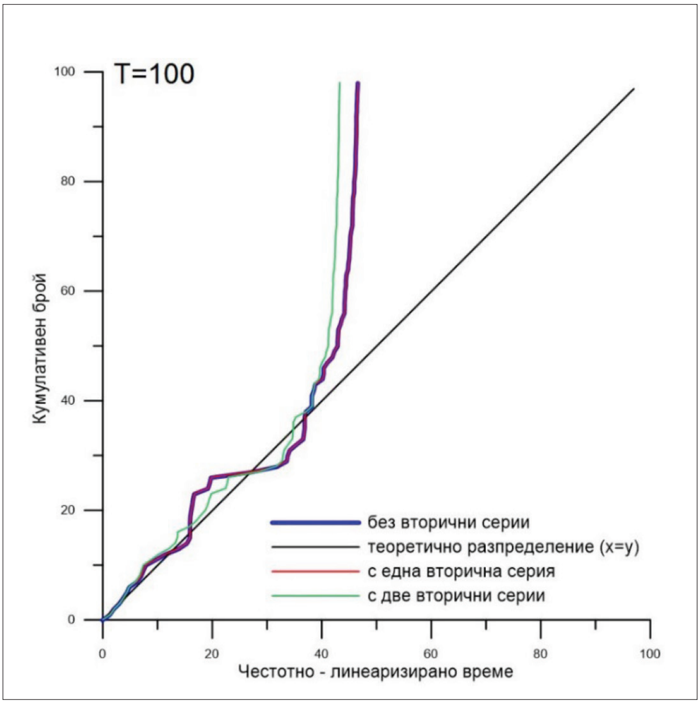
Афтършоковата поредица се представя като единична серия (без вторични поредици) чрез модифицираната формула на Omori за различни времеви интервали: очаквана продължителност, съответно T=100 дни съгласно уравнение (10). Разгледани са три случая - $1^{ви}$, (а) без магнитуден праг на афтършоковите събития; втори (б) и трети (в) съответно с M_a=1.0 и M_a=2.0. На Фиг. 2 е представено честотно-времевото разпределение на афтършоковите събития за трите разглеждани случаи. Наблюдаваното честотно разпределение се сравнява с т. нар. „теоретично“ разпределение, което в настоящия случай е в съответствие с модифицираната формула на Omori (1).

При коректен избор на параметрите K, p, c, афтършоковият процес се трансформира в стандартен Поасонов процес по честотно линеаризирана времева ос - τ. При отклонение на честотно - линеаризирано разпределение от теоретичното, се търси модел с вторична активност. На фигури 3 до 5 е представено честотно-линеаризираното разпределение на афтършоковите събития: за очакваната продължителност (T=100 дни) с и без магнитуден праг – Ma=1.0 и Ma=2.0, с и без вторични серии (разглежда се индикация за реализиране на вторични афтършокови поредици след най-силните афтършоци, събитията от 22 февруари 2018 г., с M=3.7 и от 12 май 2018 г., с M=3.4)

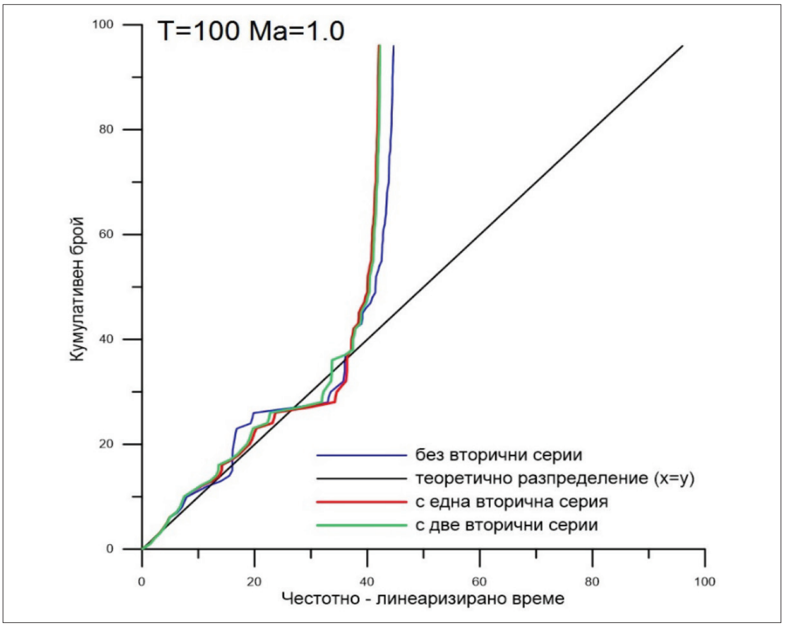
В Таблица 1 са представени стойностите на параметрите K, p, c и стойности на AIC за различните случаи.



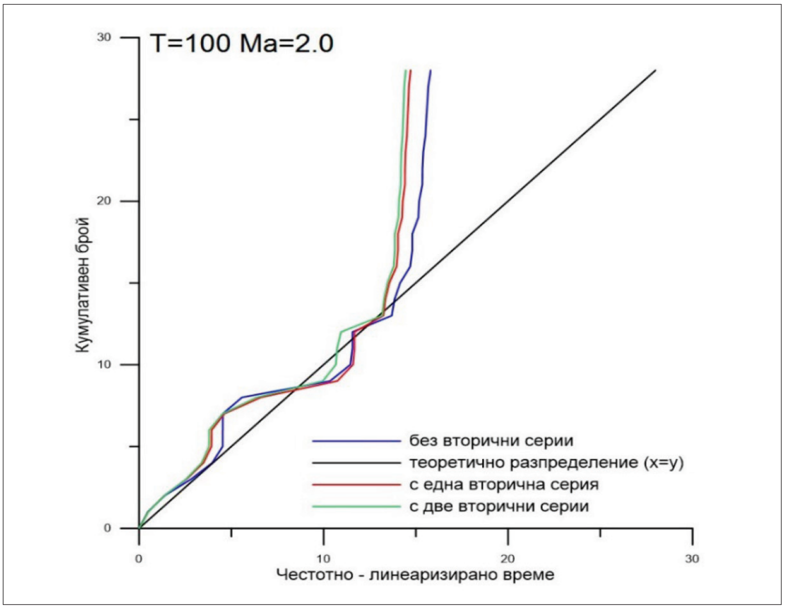
Фиг. 2. Честотно - разпределение на афтършоковите събития във времето: а) без магнитуден праг; б) Ма=1.0; в) Ма=2.0



Фиг. 3. Честотно-линеаризирано разпределение на афтършоковите събития за период T=100 дни без магнитуден праг, без и с вторични серии.



Фиг. 4. Честотно-линеаризирано разпределение на афтършоковите събития за период T=100 дни с магнитуден праг M_a=1.0, без и с вторични серии.



Фиг. 5. Честотно-линеаризирано разпределение на афтършоковите събития за период T=100 дни с магнитуден праг Ma=2.0, без и с вторични серии.

Таблица 1. Оценки на параметрите K, p, c и AIC - критерий за различни модели на поредици след земетресението от 21.02.2018 г.

Модел	**Период (T)**	**K**	**p**	**c**	**K_1**	**p_1**	**c_1**	**K_2**	**p_2**	**c_2**	**AIC**
Без вторична серия, без магнитуден праг	100	5.01	1.02	0.05							12.15
С една вторична серия, без магнитуден праг	100	3.98	1.08	0.04	0.49	1.08	0.001				-14.16
С две вторични серии, без магнитуден праг	100	3.57	1.09	0.04	0.48	1.09	0.001	0.21	1.09	0.001	-41.58
Без вторична серия, с магнитуден праг M_a=1	100	4.98	1.04	0.05							8.60
С една вторична серия, с магнитуден праг M_a=1	100	3.82	1.09	0.04	0.53	1.09	0.001				-17.72
С две вторични серии, с магнитуден праг M_a=1	100	3.44	1.11	0.04	0.47	1.11	0.001	0.46	1.11	0.04	-35.51
Без вторична серия, с магнитуден праг M_a=2.0	100	1.38	0.93	0.02							41.11

С една вторична серия, с магнитуден праг M_a=2	100	1.05	0.98	0.02	0.24	0.98	0.001				29.05
С две вторични серии, с магнитуден праг M_a=2	100	0.96	1.00	0.02	0.22	1.00	0.001	0.09	1.00	0.001	19.30

От получените оценки за параметрите K, p, c и стойности на AIC представени в Табл. 1, както и от разпределенията, на фигурите може да се направят следните заключения: 1) оценките и на трите параметъра се влияят от долния магнитуден праг M_a; 2) получените оценки на параметъра p са над 0.9 (за период от T=100 дни), което е характерно за районите на Южна България, където се предполага, че афтършоковия процес затихва значително по-бързо; 3) от честотно разпределение на афтършоковите събития може да се каже, че в първо приближение затихването на афтършоковата активност се описва добре с модифицираната формула на Omori; 4) наблюдава се преминаване от афтършокова активност към фонова сеизмичност около 84 дни след главното събитие кумулативният брой на събитията бързо се увеличава и показва значително отклонение от началния тренд; 5) най-добрият модел за времевото разпределение на афтършоковата поредица е моделът с две вторични серии и за трите разгледани случая.

Заключение

- В първо приближение затихването на афтършоковата активност се описва добре с модифицираната формула на Omori;
- Оценките на параметъра p ($0.93 \leq p \leq 1.11$), характеризиращ затихването на афтършоковата активност във времето, са около средата на интервала от стойности ($p \in [0.71;1.17]$), получени за афтършокови поредици след силни земетресения, реализирани на територията на България (Simeonova, Solakov, 1999);
- За разгледаната афтършокова поредица е установена мултиполна активност с две вторични серии (това потвърждава резултати от изследвания върху афтършоковата активност в Южна България, представени напр. в Simeonova, Solakov, 1999);
- Най-добрият модел за времевото разпределение на афтършоковата поредица е моделът с две вторични серии (най-ниски стойности на AIC) за трите разгледани случая – без магнитуден праг, с Ma=1.0 и Ma=2.0

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Temporal distribution of aftershock activity after the February 2018 earthquake occured in the area of the city of Asenovgrad, Maritsa seismogenic zone

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Abstract: The statistical analysis is applied to study the temporal distribution of the aftershock activity observed after the earthquake of February 21, 2018 with moment magnitude M_W4.7, realized in the area of the city of Asenovgrad, Maritsa seismogenic zone. Based on the assumption that the aftershocks are distributed in time as a non-stationary Poisson process, the modified Omori formula is used to estimate the parameters (K, c and p). The transformation of the time scale t to a frequency-linearized scale τ is applied to determine the best relationship between the aftershock activity and various statistical models. The decay of the aftershock activity is well described by the modified Omori formula, and a multipole activity with two secondary series is observed.