Studying Seismic Events via Satellite Interferometry for the Territory of the Balkan Peninsula

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Abstract: The prime focus of the current article is to present a pilot study in the project "Study of co-seismic deformations of the Earth's crust for the territory of the Balkan Peninsula based on satellite data" that started in December 2023. The purpose of the project is the regular monitoring of co-seismic deformations of the Earth's crust using innovative methods for processing remotely sensed data. The main task is to demonstrate the operational readiness to determine the magnitude of the deformations of the earth's surface, the size of the affected areas and to prepare maps of the displacements that have occurred. This goal will be achieved through the creation and realization of a methodology for extracting high-quality information from SAR products aimed at continuous monitoring of areas that could be considered as potential foci of strong earthquakes, integrating information from interferometric images and GNSS observations. As a result, a working prototype of an information system for monitoring and prevention of the consequences of co-seismic deformation of the earth's crust (landslides, collapses, etc.) based on freely available data provided by ESA and national agencies will be created. The core of this system is an archive that will be created with data from satellite SAR instruments for regions of the Balkans overlap in area and time registered earthquakes with a magnitude above 5.0 for the period 2015-2025. The expected results are the created deformation maps that, comparable to the position of the faults in the area and analysed with the tectonic setting.

1 INTRODUCTION

Earthquakes are natural disasters that cause damage, which is measured by human lives and destruction of infrastructural objects and elements of the urban environment. An important task after the occurrence of such an event is the preparation of a plan for overcoming them based on reliable scientific data reveal the status of the affected territory. Earthquakes most often occur at the boundaries of tectonic plates, in zones of subduction. For the region of Europe the strongest earthquakes occur around the Hellenic arc and more rarely in the interior of the Eurasian plate.

2 ANALYSIS OF THE CURRENT STATE OF RESEARCH IN THE INVESTIGATED AREA

2.1 Timeliness and Relevance of Scientific Problems Addressed by the Project

The Balkan Peninsula is one of the dangerous seismic zones on Earth, where several seismic events with a magnitude above 7 have occurred from 1900 up to now. Most of the seismic events were generated near or in the fault zone known as the Hellenic Arc located near the territory of Bulgaria and earthquakes that occur on it are often felt. In the

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past century, several destructive earthquakes with a magnitude above 7.0 have been registered on the territory of the country. Fortunately, they happened at the beginning of the twentieth century, but these events cannot be predicted and no territory is immune from the possibility of this scenario repeating itself (Solakov D. et al., 2018a.)

In this project we aim to investigate and determine the deformation of the Earth's surface that occurred in the Balkan Peninsula region after earthquakes with a magnitude greater than 5.0 Mw along the Mediterranean Seismic Zone that occurred in the last 8 years (after 2015) recorded by NOA (National Observatory of Athens) and USGS (Geological Survey USA). The main task is to demonstrate operational readiness to determine the magnitude of deformations on the earth's surface, the size of the affected area and to prepare maps of displacements. Figure 1 shows the coverage of the Mediterranean seismic zone with a fragment of the map showing the risk of seismic activity in Europe.

Bulgaria has registered high seismic activity in several areas. The most risky are: Kresnenska, Plovdivska, Sofiiska, Gornooryakhovska and Shablenska zones. The strongest earthquake had a magnitude of 7.8 on the Richter scale and was located in the valley of the Struma River in 1904. The last strong earthquake was in the area of Pernik on 22.05.2012 with a magnitude of 5.8 on the Richter scale near Sofia and was felt by most of its residents. The last stronger earthquake in Bulgaria was in 2012 with a magnitude Mw of 5.6 near the capital Sofia (Solakov D. et al., 2018b).

The last event that shook the whole world was the earthquake doublet on February 6, 2023. in southern Turkey near the northern border of Syria with magnitude M 7.8, which was followed later by an event with magnitude M 7.5 at about 90 km north of the first. The location of the first earthquake is near the triple junction of the Arabian and African plates and the Anatolian block. In scientific community it is widely accepted that seismicity in Turkey is due to the relative movement of three large tectonic plates (Arabian, Eurasian and African), as well as one smaller tectonic block (Anatolian).

The geological development of the region is the result of several boundary interactions between these plates, which include subduction, large scale faulting, compressional mountain uplift, and extension of the Earth's crust. When the African and Arabian plates converge the Eurasian plate leads to the closure of the Mediterranean Sea and at the same time is the reason for the westward movement of the Anatolian block.

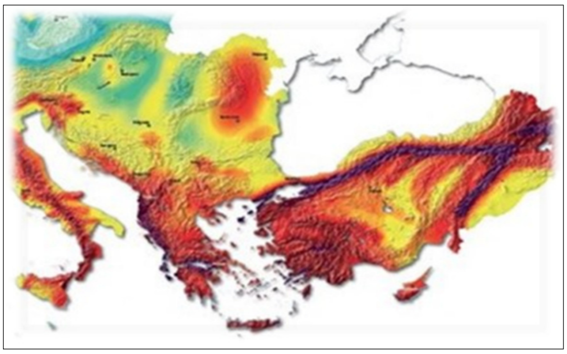


Figure 1: The Mediterranean Seismic Zone.

This movement is taking place mainly along the fault lines on the two Anatolian fault lines – Northern and Eastern. (Kalafat et al., 2021) The westward movement of the Anatolian block is mainly carried out by the North Anatolian fault system evidenced by the large number of earthquakes registered during the second half of the last century. On the other hand, the same block moves in a southwest direction towards the Arabian Plate, as the movement is realized along the Eastern Anatolian, where also earthquakes with magnitude above 7 were recorded. Based on event from 27.01.2020 as well as other ones since the beginning of the century it can be said that the Eastern Anatolian fault is the more active (Utkucu M. et al., 2023), (Reitman et al., 2023)

Co-seismic deformations of the Earth's crust occur at the time of a strong seismic event, with a magnitude above 5.0 on the Richter scale and have manifestations on the Earth's surface at points near to the epicentre of the event. They are determined mainly by the satellite observations using technologies based GNSS and SAR data, that was applied successfully in the recent years.

The basic way to register and measure the strength of an earthquake is through the use of a seismic station, equipped with different types of seismic receivers. In the last decade seismic stations are supplemented by ground-based networks of GNSS receivers, which provide the possibility to determine displacements, occurring at the Earth's surface and the propagation of seismic waves.

The Global Navigation Satellite System (GNSS) is used to study the velocity field of the Earth's crust, as well as Earth's deformations, attributed to seismic, volcanic, geological or anthropogenic activity. Using the GNSS method it is possible to determine the 3D vector of displacement on the earth's surface and calculate errors of 2–3 mm for the horizontal and 5–8 mm respectively for the vertical components confined to the position at the point of measurement.

By processing data from Earth observation satellites registering data with radar instruments by DinSAR method provides greater spatial coverage, but information about displacements is in the line-of-sight (LoS) on the antenna. Additional analysis is necessary to obtain all components of the Earth's motion vector. The main sources of data that are planned for use are the SAR products from the Sentinel-1 mission thus achieving extensive territorial coverage. This allows preparation of maps that reveal the scale of deformations on the Earth's surface. Along with these data other data for the epicentre of earthquakes and for the established faults in the research areas are used as well. Due to the fact that the DInSAR method requires the availability of two radar images obtained during a time interval between the registrations of the SAR data the mentioned maps reflect the cumulative effect of all seismic events in this interval. This means that it is not possible determine the contribution of a single event to the produced displacements.

2.2 Current State of the Research in the Investigated Area

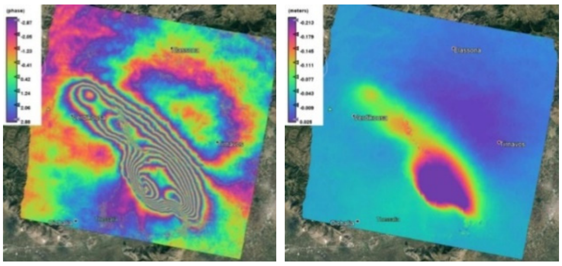
As mentioned, the Balkan Peninsula, and in particular the territory of Bulgaria and Greece, show active tectonics and seismicity. Currently advanced space geodetic techniques and methods are used for better understanding of long term geological and geophysical processes. Based on the analysis and processing of GNSS data, a number of studies show the recent activity of the region and try to give a reasonable and adequate interpretation of the obtained results regarding the processes of movement of the earth's crust in the region (Burchfiel et al ., 2006), (Burchfiel et. al., 2008), (Georgiev et. al., 2013), (Kotzev et.al., 2006), (Milev, Dabovski, 2006) (Matev, 2011), (Reilinger and al., 2010), (Vassileva, Atanasova, 2014), (Zagorchev, 2011) and others.

On July 20, 2017, an earthquake occurred near the island of Kos with Mw 6.6 and a depth of 2 km. The epicentre of the earthquake is located in the Aegean Sea, about 1 km south of the uninhabited island of Karaada and also the Greek islands of Kos and town Bodrum with in the southwestern part of Turkey was affected. Maps of the displacement were created and the values of the southern time sinking of Karaada Island in the LoS direction from descending and ascending orbits were determined (Atanasova § Nikolov 2018); (Atanasova § Nikolov 2019).

The surface deformations that occurred after an earthquake on October 25, 2018 located about 45 km southwest of the island of Zakynthos with Mw 6.8 and a depth of 10 km (Ganas et al., 2020) (Nikolov et al., 2021) were also determined based on the prepared interferograms. On November 26, 2019, the most devastating earthquake in the last 40 years for the region occurred in the north-western part of Albania, which was the second such event in a period of three months and was located about 8 km northeast of the port city of Durres. The interferometric results are presented in (Nikolov et al., 2020) and (Nikolov et al., 2021).

The devastating earthquake that struck Croatia on December 29, 2020 had a magnitude of 6.4 on the Richter scale. This is the biggest earthquake in Croatia recorded in the last century. An earthquake of similar magnitude occurred in 1880 near Zagreb. Three earthquakes of magnitude 6 and greater have occurred since 1900 to date within 200 kilometres of the epicentre of the said earthquake. The main shock and most of the aftershocks are located on the Petrinja Fault, which is well described in the European Database of Seismogenic Faults (EDSF) (Basili R et al., 2013). This phenomenon is investigated by InSAR data and supplemented with seismological results by using Okada method (Dimova, Raykova 2023).

The surface deformations that occurred after an earthquake of Mw 6.0, which occurred on March 3, 2021, 20 km northwest of Larissa, Greece were determined. (see fig 2). Usually, using the applied method, the total changes of the Earth's crust are registered for the period between two passes of the satellites, which for the Sentinel mission (for 2021) is a minimum of 6 days (Atanasova § Nikolov 2021) (Atanasova et al., 2021). In the (Dimova, Raykova 2023) comparison of the results from pre-calculated vertical (up–down) and horizontal (E–W) displacements and the theoretical results obtained from Okada`s model was made and good coincidence for both of the suggested focal echanisms for Larisa earthquake was found. (Dimova, Raykova 2023) calculated three types of geometry for the seismic fault near Larissa varying the length, the width and the slip over the fault.



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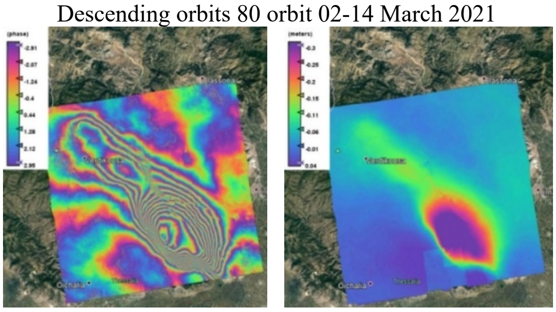


Ascending orbits 175 orbit 02-14 March 2021

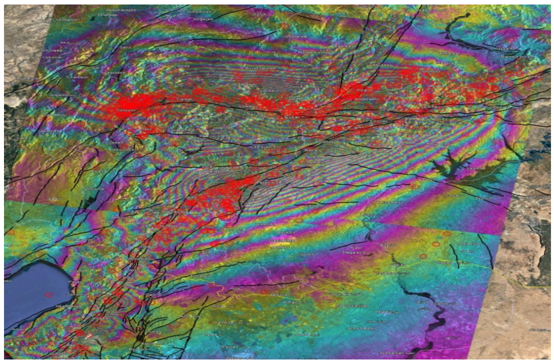
Figure 2: Interferometric images of the area of the Larissa earthquake and maps of the deformations along the LoS direction determined by the two types of orbits.

The area covered by the displacements is quite similar, although the Okada model underestimates a little the values obtained by the DInSAR procedure. It can be due to the uncertainties of the input parameters used in the theoretical computation of the displacement as well as the simplifications of the Okada's model.

The latest presented results obtained as a result of the processing of SAR data, based on which movements of the Earth's surface caused by the series of earthquakes that occurred in the border region between Turkey and Syria were detected. The latest challenge is to determine the deformations of the wide areas, following the two devastating earthquakes of magnitude M 7.8 and M 7.5 on February 6, 2023. The earthquakes occurred in the East Anatolian Fault Zone, west of Gaziantep, Turkey.

The earthquake was followed by intense aftershocks, the effect of which was proven after interferometric processing of SAR data from the European Space Agency's Sentinel-1 mission and revealed the size of the affected area and the magnitude of the deformations that occurred after the earthquakes.

The maps created are combined data from several sources: event epicenters from EMSC and active faults from EDAF (Basili R.,, et al., 2013) both considered to be the driving forces of ground motions. SAR data, used to obtain information indicating the actual surface displacements. It should be emphasized that the mentioned information does not reflect the consequences of one seismic event, but the effect of all earthquakes that occurred in the studied region between the dates of registration by the SAR instrument (Atanasova et al., 2023), (Nikolov & Atanasova, 2023).



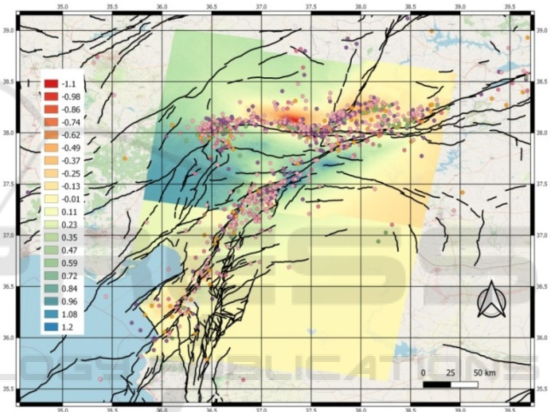


Figure 3: Interferometric images of the area of the Turkey earthquake registering the vertical deformations by descending orbit SAR data, earthquake area and epicentres, active faults.

3 OBJECTIVES AND HYPOTHESES FOR DEVELOPMENT OF THE PROJECT

The purpose of this study is the regular monitoring of seismic deformations of the Earth's crust using innovative methods. The main task is to demonstrate operational readiness to determine the magnitude of the deformations of the Earth's surface, the size of the affected areas and to prepare maps of the displacements that have occurred. This goal will be achieved through the creation and realization of a methodology for extracting high-quality information from SAR products aimed at continuous monitoring of areas that could be considered as potential foci of strong earthquakes, integrating interferometric images (IFI) and GNSS data. As a result, a working prototype of an information system for monitoring and prevention of the consequences of co-seismic deformation of the Earth’s crust (landslides, collapses, etc.) based on freely available data provided by ESA and national sources will be created.

Achievement of the set goal is realized through interrelated and complementary scientific and scientific-applied tasks:

– Creation of a catalogue with earthquakes in the Balkan Peninsula having magnitude of 5.0 or more Mw
– Creation of automated methodology for extraction of data from SAR and their unified processing for geocoding.
– Obtaining the coordinates and speeds of the permanent GNSS stations coordinates and velocity of permanent GNSC stations from the national network of NIGGG and freely available data from other types of GNSS stations for the territory of the Balkan Peninsula.
– Analysis of GNSS time series to register changes (jumps) due to seismic events
– Determination of the deformations of the Earth’s crust by the method of Okada on geophysical and seismic data and their comparison with the results obtained from the SAR data
– Formation of a data base for the investigated areas , including IFI , geodetic data from permanent stations, seismic and geophysical data, as well as carrying out spatial analysis regarding the presence of deformational processes ;
– Determining the possibility of searching for a connection between the location of the epicentre of an earthquake and the tectonics of the research area, lithospheric plates and the possibility of predicting the occurrence of an event based on changes in the magnetic field or other geophysical factors.

After the implementation of the above formulated tasks, it will be reached the fulfilment of the second goal of presenting the information system not only among the scientific community, but also before the national and local authorities, the academic community and other interested parties. In this way we hope to give them the opportunity to use a new tool to solve the problem before it occurs on a specific disaster of natural or anthropogenic character.

One of the scientific tasks envisaged to be solved include the development of methodological approaches for the comparison of the results of the joint processing of interferometric images from the SAR, the data from the permanent GNSS stations and the obtained results for the deformations of the Earth’s crust by Okada's method on geophysical and seismic data.

After the primary processing of the three types of data, their fusion and subsequent spatial analysis in a GIS environment is foreseen. In this way, the degree of preparedness of national and local authorities, as well as society as a whole, will be increased, the prevention will improve and the consequences of this kind of disasters overcomed.

4 METHODS, RESEARCH EQUIPMENT AND TECHNIQUES

4.1 Global Navigation Satellite Systems

Global navigation satellite systems (GNSS) consist of a ground network of receivers, space and control segments. The use of GNSS for seismic monitoring in Bulgaria and the Balkans has great potential, using data from GNSS networks with free access such as: international- ITRF, IGS; Regional - EPN on EUREF; National GNSS network.
Registration of seismic movements of the Earth's crust on the territory of Bulgaria on the basis of data received from permanent GNSS networks can be used for operational seismic monitoring and supplementing information related to the occurrence and tracking of events, thus delivering information on the Earth's crust movements at Balkan Peninsula. In the present project it is anticipated to use the data from the National Geodetic Network, maintained by NIGGG-BAS.

4.2 Bulgarian Seismological Network

NIGGG-BAS runs the Bulgarian seismological network-NOTSSI (National Operative Telemetric System for Seismological Information). NOTSSI was founded at the end of 1980. The network comprises today 17 permanent seismic stations and two local networks. In 2005 the modernization of the seismological network was performed. The overall objective for the NOTSSI is continuous monitoring of seismicity on the territory of Bulgaria and adjacent areas within the Balkan region. After the modernization, NOTSSI became a world-class digital network providing reliable, real-time seismic monitoring and rapid earthquake information to both scientific communities and authorities in Bulgaria for seismic risk mitigation. Recently developed Methodology for analysis, assessment and mapping of the seismic risk of Bulgaria; and the new seismic hazard assessment for Bulgaria are based on the high quality seismological information.

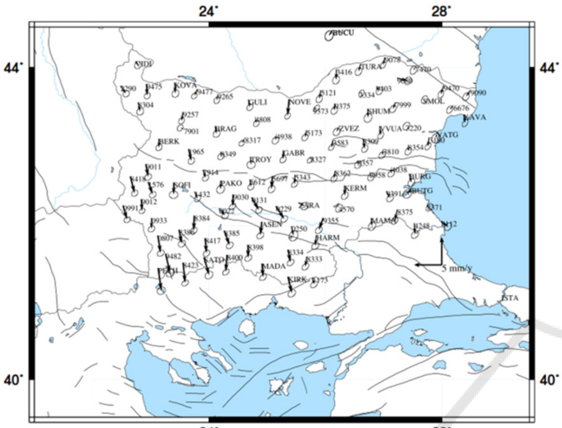


Figure 4: The horizontal velocities of the points of the Basic class of the State GPS network - 2014-2018. https://ngic.bg/.

The area subject to research in the proposed project covers the Balkan Peninsula, which justifies the need for additional GPS/GNSS infrastructure in it, since successful monitoring of modern crustal movements implies: permanent stations with sufficient density and GNSS points.

4.3 Differential Interferometry

Differential interferometry (DinSAR) is a method for processing radar data from synthesized aperture, derived from remote Earth observation, that can be used to quantify small displacements on the surface. For example, using data from the Sentinel-1 satellite and applying DInSAR, mapping of topography over a large area or registration of movements on the Earth's surface is performed. The DInSAR method is based on using two images of the phase signal backscattered from the Earth's surface obtained for the same region at different times. In processing the SAR data, co-registration of the two SAR images is performed and then a differential interferogram is generated, which shows the magnitude of the deformation using the change in the phase signal. The horizontal and vertical movements are registered in LoS vector that needs to be decomposed. At the stage of formation of the interferogram a digital terrain model (DEM) with a resolution of 1 arcsec is used, since it is essential that the spatial resolution of the final interferometric image (IFI) be as high as possible.

4.4 Okada's Method

The surface displacement, due to the elastic deformations of the earth's crust, after generated earthquake was obtained as an analytical solution of Okada's formulas (Okada, 1985, 1992).
The co-seismic deformation is calculated as a function of the geometrical parameters of the fault and the elastic properties of the medium. The geometry of the modelled faults was calculated using the formulas of Mai and Beroza (2000) for the relationship between the seismic moment of a given earthquake and its magnitude.

4.5 GIS Data

Initially, a register will be created of all registered earthquakes with a magnitude above 5.0 in the last eight years (after 2015) for the Balkan region and neighboring territories. This database will continue to be populated throughout the duration of the project. Based on it, the location and time interval of the seismic event will be identified, which will make it possible to proceed to the creation of the specialized archive with SAR data.
Here, additional terrain elevation data will be required, so DEM data must be available from external sources, such as SRTM or ASTER repositories, and must be included in the local archive already created. After that, it is planned to integrate the IFI and GNSS data from the geodynamic network. Here, both data types must be in the same coordinate reference system and projection.
Based on this, we will prepare displacements maps in GIS layers for the Balkan region in a time interval of 6 or 12 days, based only on IFI, which will allow us to obtain the movements that occurred during the earthquakes.

5 CONCLUSIONS

The purpose of the project is formulated on the basis of previous scientific and scientific applied research on the team. The implementation of the project will help to increase the quantity and quality of fundamental scientific research related to problems of regional and national importance. The tasks of the project include both the intensification of the relationship between science and education and society as a whole and the enhancement of the quantity and quality of the internationally visible scientific output.

The public challenges to which the project is focused are minimizing the damages from natural disasters and accidents and for protecting the environment. The project also responds to them by studying geodynamic processes in the Earth's crust and providing up-to-date information about them.

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REFERENCES

Atanasova M., Nikolov H., Protopopova V., (2018) Determining the deformations of the earth's crust after an earthquake using DInSAR. *IX National Conference on Geophysics - CD*, 2018, ISSN:1314-2518 (in Bulgarian)

Atanasova M., Nikolov H., Protopopova V., (2019). DInSAR in displacement detection after seismic events. *Proceeding 10th Congress of Balkan Geophysical Society, 18-22 September 2019, Albena Resort, Bulgaria, EAGE, 2019*, DOI: 10.3997/2214-4609.201902642, 1-4. SJR (Scopus):0.11

Atanasova Mila, Nikolov H., (2021) Determining the deformations of the earth's crust using DInSAR that occurred after the earthquake in the Larisa region of March 3, 2021. *10TH NATIONAL CONFERENCE ON GEOPHYSICS* / National Institute of Geophysics, Geodesy and Geography, BA Sofia, CD 10, X, Society of Geophysicists in Bulgaria, 2021, ISSN:1314-2518, 1-8, (in Bulgarian) https://www.niggg-bas.com/periodicals/x-national-geophysical-conference-4th-june-2021/n3/

Atanasova Mila, Nikolov Hristo, (2022) A STUDY OF SEISMIC DISPLACEMENTS IN THE BALKANS FROM SATELLITE DATA, *Proceeding XXX International symposium on modern technologies, education and professional practice in geodesy and related fields*, Sofia, 02 – 04 November 2022 ISSN:2367-6051, 1-11

Atanasova M., Nikolov H., Oynakov E. (2021) Co-Seismic Surface Displacements After The Earthquakes In Larissa, 3 March 2021, Derived By Dinsar. *Proceedings of 21th International Multidisciplinary Scientific GeoConference SGEM 2021, Volume: 21, Book number: 2.1, International Multidisciplinary Scientific Geoconference, 2021*, ISBN:1314-2704, ISSN:978-619-7603-22-4, DOI:10.5593/sgem2021/2.1/s10.64, 521-528.

Atanasova M, Raykova P, Nikolov H., (2023) Determining the Deformations of the Earth's Surface after the Earthquakes in Turkey-Syria of 06 February 2023 - Initial Results. *Comptes rendus de l'Académie bulgare des Sciences, 76, 4, Bulgarian Academy of Sciences,* 2023, ISSN:1310–1331, DOI:https://doi.org/10.7546/CRABS.2023.04.07, 554-562

Atanasova Mila. (2023) Determination of coseismic deformations in the Balkan Peninsula area based on SAR data. XI National Geophysical Conference, 9th June 2023. *Proceedings of the XI National Geophysical Conference, 9th June 2023., XI,* NIGGG-BAS, CD, 2023, DOI: https://doi.org/10.48368/BGS-2023.1.N12 (in Bulgarian)

Basili R., V. Kastelic, M. B. Demircioglu, D. Garcia Moreno, E. S.Nemser et al. (2013) *The European Database of Seismogenic Faults (EDSF) compiled in the framework of the Project SHARE,* https://doi.org/10.6092/INGV. IT-SHARE-EDSF.

Burchfiel, B.C., King, R.W., Todosov, A., Kotzev, V., Durmurdzanov, N., Serafimovski, T., Nurce, B. (2006) GPS results for Macedonia and its importance for the tectonics of the Southern Balkan extensional regime. *Tectonophysics*, 413, 239-248

Burchfiel, B.C., Nakov, R., Dumurdzanov, N., Papanikolaou, D., Tzankov, T., Serafimovski, T., King, R.W., Kotzev, V., Todosov, A., Nurce, B. (2008) Evolution and dynamics of the Cenozoic tectonics of the South Balkan extensional system. *Geosphere, 4*, 919-938, doi:10.1130/GES00169.1 1.

Copernicus. Sentinel-1 data 2017 to 2021. Retrieved from ASF DAAC (8 Nov 2019), Processed by ESA. Available online: https://asf.alaska.edu/ (accessed on May 2021).

Dimova, L. R. Raykova. (2023) Complex analysis of earthquake deformations using SAR images: Examples from Croatia and Greece. *Journal of Physics: Conference Series (JPCS).* 2668(1):012011, DOI: 10.1088/1742-6596/2668/1/012011

Ganas, A., P. Briole, G. Bozionelos, A. Barberopoulou, P. Elias, V. Tsironi, S. Valkaniotis, A. Moshou, I. Mintourakis, (2020) The 25 October 2018 Mw = 6.7 Zakynthos earthquake (Ionian Sea, Greece): A low-angle fault model based on GNSS data, relocated seismicity, small tsunami and implications for the seismic hazard in the west Hellenic Arc, *Journal of Geodynamics*, 137, 2020

Georgiev, I., Dimitrov, D. and Botev, E. (2013) Crustal Motion Monitoring in Bulgaria and Surrounding

Regions by Permanent GPS Array. *Proceedings of 7th Congress of Balkan Geophysical Society, Tirana, Albania, 7-10 October 2013, 5*

Kalafat D., A. C. Zülfikar and S. Okuyan Akcan (2021) Seismicity of Turkey and Real-Time Seismology Applications in Determining Earthquake Hazard, *Academic Platform Journal of Natural Hazards and Disaster Management, vol. 2, no. 2, pp. 96-111*, Dec. 2021, doi:10.52114/apjhad.1039670

Kotzev, V., Nakov, R., Georgiev, Tz., Burchfiel, B.C., King, R.W. (2006) Crustal motion and strain accumulation in western Bulgaria. T*ectonophysics*, 413, 127-145.

Mai, P. M., Beroza, G. C., (2000), Source scaling properties from finite-fault-rupture models*, Bull. Seismol. Soc. Am.*, 90, 3, 604-615.

Matev, K. (2011) GPS constrains on current tectonics of southwest Bulgaria, northern Greece and Albania. Thesis, Doctor of university of Grenoble, 203.

Milev, G. and Dabovski, C. (Eds) (2006) Geodynamics of the Balkan Peninsula, *Monograph, Reports on Geodesy.* Warsaw University of Technology, Institute of Geodesy and Geodetic Astronomy, 647.

Nikolov H., Atanasova M., Protopopova V.,(2021). Application of satellite SAR data to detect deformations of the Earth's crust after earthquakes. *Proceedings of 2nd National Workshop with International Participation on COPERNICUS*, S, pace Research and Technology Institute - Bulgarian Academy of Sciences (SRTI-BAS), Sofia, Bulgaria, 2021, DOI:10.5281/zenodo.6497513, 25-37

Nikolov H., Valentina P., Atanasova M.(2020) Studying seismic events via satellite interferometry. Proceedings Volume 11524, Eighth International *Conference on Remote Sensing and Geoinformation of the Environment (RSCy2020);* Paphos, Cyprus, 15241B, 11524, SPIE 2020, *Proceedings of SPIE - The International Society for Optical Engineering,* 2020, 11524, 115241B, 2020, ISBN:978-151063857-0, ISSN:0277786X, DOI:10.1117/12.2570676, 1-16.

Nikolov, H., & Atanasova, M. (2023). Co-seismic ground motions from earthquakes in Turkey-Syria as registered by SAR data. *XI National Geophysical Conference,* 9th June 2023. https://doi.org/10.48368/BGS-2023.1.N11 (in Bulgarian)

Okada, Y., 1985, Surface deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am.,* 75, 4, 1135-1154.

Okada, Y., 1992, Internal deformation due to shear and tensile faults in a half-space, *Bull. Seismol. Soc. Am.,* 82, 2, 1018-1040.

Solakov, DSimeonova. S., Raykova P., Aleksandrova I (2018a). Empirical Relations Converting Md and Mp Magnitudes Applied In Bulgarian Seismological Routine Practice To Moment Magnitude. *Comptes rendus de l'Acad'emie bulgare des Sciences,* 71, 8, DOI:10.7546/CRABS.2018.08.09, 1076-1085

Solakov, D., Simeonova, S., Raykova, P., Aleksandrova, I (2018b). Seismological analysis of the low frequencies Mw5.6 earthquake in Sofia Seismogenic zone. *Procc. 9th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology,* PATA, 267-270.

Reilinger, R., McClusky, S., Paradissis, D., Ergintav, S. and Vernant, Ph.(2010) Geodetic constraints on the tectonic evolution of the Aegean region and strain accumulation along the Hellenic subduction zone. *Tectonophysics, 488,* 22-30.

Reitman N, et al., (2023) Preliminary fault rupture mapping of the 2023 M7.8 and M7.5 Türkiye Earthquakes. DOI: https://doi.org/10.5066/P985I7U2

Utkucu M. Et al., A preliminary report on the 2023 Gaziantep (Mw=7.7) and Elbistan (Mw=7.5), earthquakes in Southeast Türkiye, February 2023, doi: 10.13140/RG.2.2.17088.40963

Vassileva, K. and Atanasova, M. (2014) Study of transition boundaries in Bulgaria from GPS. *International symposium on modern technologies, education and professional practice in geodesy and related fields*, Sofia, 06-07 November, 2014, 8.

Zagorchev, I. (2011) Cenozoic Block Rotations in the Balkan Peninsula. *Proceedings of 3rd nternational Symposium of the Black Sea region*, 1-10 October, 2011, Bucharest, Romania, 220-222

https://scihub.copernicus.eu/

http://step.esa.int/main/toolboxes/snap/

https://storymaps.arcgis.com/stories/355bfc8b3c5941e683d4f258e8fb2dfa