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SPACE GEODESY DATA IMPLEMENTATION FOR EARTH SYSTEM GEODYNAMICS MONITORING: A CASE STUDY OF THE AEGEAN MICROPLATE

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Abstract

The advances in geodesy that are continually occurring allow the science of investigating the Earth's shape and size to be applied to the observation of its geodynamics as well. Space geodesy and remote sensing methods enable the desired phenomenon to be observed with high precision and at different scales, where the phenomenon can be global or local in nature. By tracking changes in the position of unique points on the Earth's surface using space geodesy methods (GNSS – Global Navigation Satellite System, VLBI – Very-long Baseline Interferometry, SLR – Satellite Laser Ranging, DORIS – Doppler Orbitography and Radiopositioning Integrated by Satellite), it is possible to indirectly track the movement of the Earth system and describe changes, anomalies and their evolution over time.
The main objective of the article is to define and describe the tectonic plates' movement based on the selected approach and analysis, compare the results with conventional tectonic boundaries definition and support the anomalous outcomes for discrete locations by ongoing tectonic phenomena over the time period under study. By implementing space geodesy data into deformation analyses, the aim is to demonstrate the geodynamic contribution of space geodesy in studying and monitoring the geodynamics of the Earth system.

Keywords:

Space geodesy;
Geodynamics monitoring;
ITRS;
Tectonic plates' movement

1 Introduction

Studying the dynamics and kinematics of the Earth represents an important step towards understanding and explaining a significant amount of geodynamic, geophysical, and geological phenomena occurring on or within the Earth. Research related to these phenomena involves interdisciplinary geoscientific exploration and study. The progress in the field of geodesy in the 1980s marked the beginning of new possibilities for studying the Earth – its shape, size, and geodynamics. Methods of space geodesy and remote sensing of the Earth (RS) have become fundamental pillars of geoscientific exploration, and the data provided by these methods are applied in examining various phenomena from global to local scales and resolutions. The principles and theoretical backgrounds related to the space geodesy techniques are presented in many scientific research papers. Many credible facts and information may be found for example in [1-4].

The Earth is highly dynamic, and changes occur constantly. The nature of these movements is unpredictable and irregular in many cases. It is precisely the methods of space geodesy and remote sensing of the Earth that currently allow monitoring the desired phenomenon with high precision, without direct interaction of the scientist with the site, depending on the nature of the studied phenomenon. Continuous measurement enables the detection and prediction of changes that may lead to destructive or fatal consequences [5]. Any reconstruction helps understand the causes of the emergence of the given phenomenon/movement.

The highly precise measurements of today's satellite methods allow determining the position of points with millimetre precision [6-9], making it possible to record very small and seemingly insignificant changes in the Earth system using geodetic methods. To accurately and reliably record these changes, it is essential to have a global and long term stable reference system, the so called geodetic reference system. The creation and maintenance of such a highly precise, stable, and reliable geodetic reference system are one of the primary contributions of space geodesy to monitoring the geodynamics of the Earth's system. Among the methods of space geodesy that contribute either to the creation of global geodetic systems or to the monitoring of geodynamic phenomena are GNSS, SLR, LLR (Lunar Laser Ranging), DORIS, VLBI. Data provided by geodetic and other satellites as part of remote sensing of the Earth, in combination with data provided by space geodesy methods, contribute to monitoring the geodynamic processes of the Earth system.

Through exact estimations and progressed innovations, geodesy gives profitable information that contribute to our understanding of different environmental processes. Monitoring of individual components of the Earth system requires adaptation of the form of data collection depending on the nature of the phenomenon being monitored. For the purpose of monitoring the change in mean sea level of the world ocean, this is e.g. satellite altimetry - accurately measure sea surface height, or Tide Gauges and GPS - In order to distinguish between sea level rise and vertical land motion, tide gauges and GPS readings can be used in conjunction to precisely monitor local variations in sea level as well as land subsidence or uplift. Gravity measurements via missions and satellites like GRACE (Gravity Recovery and Climate Experiment) track variations in the Earth's gravitational field, which can be utilized to track significant shifts in glaciers and ice sheets. Understanding polar ice loss and how it contributes to sea level rise is essential. Apart from gravity measurements, GPS networks track the movements of glaciers and ice sheets as well, thus providing new information on the velocity and deformation parameters of monitored ice masses. Post-seismic deformation method (PSD) is based on the geodetic measurements that track and monitor the deformation od the Earth’s surface after the tectonic activity in the form of an earthquake. PSD models consequently enable to understand the redistribution of stress and risk of potential aftershocks. Geodesy has an irreplaceble place within the water resources and drought tracking. Geodetic missions (GRACE, GFO) measure variations in the Earth's gravitational field to offer information on changes in groundwater storage. This is critical for water management, monitoring droughts, and aquifer depletion. Another approach in the form of tracking the surface and subfurface water movement provide information about the impact of environmental changes on water availability. Geodesy contributes also to climate models by implementing geospatial data into climate models and thus improves predictions related to extreme weather or global warming.

The changes that occur are influenced by many factors – anthropogenic activity, climate change, processes that have been occurring on the surface, under, or above the Earth's surface to some extent and intensity [10]. Among the basic components of the Earth system that undergo changes are the atmosphere, water, oceans, glaciers, and the Earth as a solid body [6]. Inside the Earth, there are processes and phenomena that have been constantly changing for millions of years, such as convective movements in the Earth's mantle responsible for geodynamic phenomena such as earthquakes, tsunamis, tectonic, or volcanic activity [11,12]. In the oceans, there is a transfer of a huge amount of energy and heat through ocean currents [13,14]. The hydrological cycle reflects seasonal periodic processes as well as trends in precipitation, evaporation, and runoff, which ultimately lead to varying amounts of water resources in a given region [15-19]. All these subsystems are closely interconnected with each other and with the atmosphere. This close interaction also complicates the understanding of this complex Earth system because any change in one subsystem can have huge consequences in another.

Many researches has dealt with the implementation of geodesy techniques (space and satellite geodesy, remote sensing, terrestrial observation a data acquisition etc.) and their output data within the monitoring of the Earth system, its subsystem and geodynamic processes so far. Satellite altimetry data application may, for example, concern the topic on lithosphere properties [20] or vertical land motion detection [21]. Other research focuses on the application and interpretation of geodetic data in tracking the world water supplies [22,23]. All geodynamic processes of the Earth system have an impact on the transfer of masses, thus affecting not only changes in the Earth's gravity field, but also the movements of the lithospheric plates. This tectonic activity, in the form of the tectonic plates' movemnet, manifests itself in many phenomena such as earthquakes, volcanic activity and tsunamis. However, the observation of seemingly unrelated manifestations of the geodynamics of the Earth system has shown significant connections. For example, as shown in [24], by observing changes in the Earth's gravitational field, it is possible to hypothesize the occurrence of tectonic activity (earthquakes), which have a direct impact on the movement and deformation of the lithosphere.

The study of Earth system geodynamics, specifically the movement and deformation of tectonic plates, has so far been pursued by many scientific teams with the unique approach of applying and implementing available, not only geodetic, data to model and interpret lithospheric dynamics and its changes. In [25] authors used space geodesy data to determine and analyze tectonic plates' movement and also compared the space geodesy data with already existing predictions of plate motion model. Comparing space geodetic data with predictions from models of instantaneous plate motion shows that average plate velocities over a few years are comparable to average plate velocities over millions of years. Space geodetic information will provide insights into numerous critical unresolved issues regarding the movement and behavior of large plate boundary areas. These data will be useful in deciding whether the kinematics of plate boundary zones are best described by a continuum model, a multiple-microplate model, or a combination of both. Another research [26] provided an insight into crustal deformation measurements resulting from space geodesy data and their implementation into earthquake hazard studies. According to space geodesy mapping of continental deformation, the majority of interplate displacements are located at the boundaries of the major tactonic plates (Aegean plate, Hellenic Subduction Zone, San Andreas falut etc.). In [27] spatial and temporal variations of earth systém deformation is analyzed and interpreted using space geodesy data, especially GPS networks and InSAR observations. According to authors, Geodetic measurements are the main source of data that can detect the crustal deformation caused by earthquake and fault activity during locking stage.Observing changes and developments happening within the Earth system, whether ceaselessly or occasionally, speaks to advance in understanding the Earth as a framework, much obliged to the observing and examination of its subsystems. The case study objective is to demonstrate the geodynamic contribution of space geodesy together with the deformation-analytic contribution. Therefore, the primary input data consists of the spatial coordinates of observational and colocation stations of individual space geodesy techniques (GNSS, VLBI, SLR, DORIS) and the changes in these coordinates over time (Figure 1).

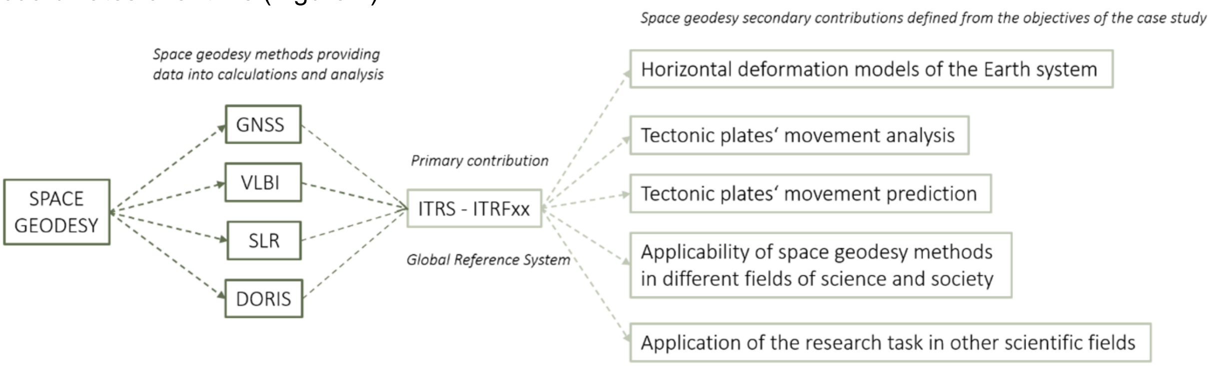

Fig. 1: Space geodesy contributions (Authors)

Many recent researches and scientific publications [28,29] point out the indispensable application of space geodesy in many disciplines, especially scientific. However, the interpretation and implementation of the results, which roots lay in space geodesy approach, may link the seemingly unrelated areas.

The availability of this data over a relatively long time interval enables the analysis of the movement of the Earth's surface, i.e., lithospheric plates, mediated based on the change in position of monitored permanent stations. This hypothesis constitutes the basis of the research task and determines the way of designing the methodology for solving the task.

Fig. 2: Space geodesy contributions (Authors)

By applying data from space geodesy, it is not only possible to monitor, describe, and better understand the Earth's system and its changes over time, but also to utilize analogous situations and data interpretations in the occurrence of natural disasters (such as earthquakes, tsunamis, etc.), thus predicting the possible occurrence of such situations and protecting the lives of all living organisms, as well as anthropogenic structures and assets (Figure 2).

The aim of the research task is to apply existing data obtained from long term and permanent observation of the Earth's surface by space geodesy methods to global or local monitoring of horizontal deformations of the Earth's surface using innovative approaches and visualizations. This approach is applied to one of the most observable tectonic activities - the movement of tectonic plates. Based on the proposed methodology and the application of space geodesy data, the aim is to interpret, in a mediated way, the movement of tectonic plates, which is the subject of investigation by different scientific disciplines (seismology, teleseismology, tectonics and others).

2 Data and methods

The methodology of solving the research task is based on the implementation of space geodesy data into calculations and analyses so that the resulting interpretation allows the assessment of the movement of lithospheric plates indirectly based on the change in the position of observing stations over time. In order to obtain such resulting information, it is necessary to establish several hypotheses and to obtain parameters describing the horizontal deformation of the Earth's surface from the spatial coordinates of the observing stations and their changes in time.

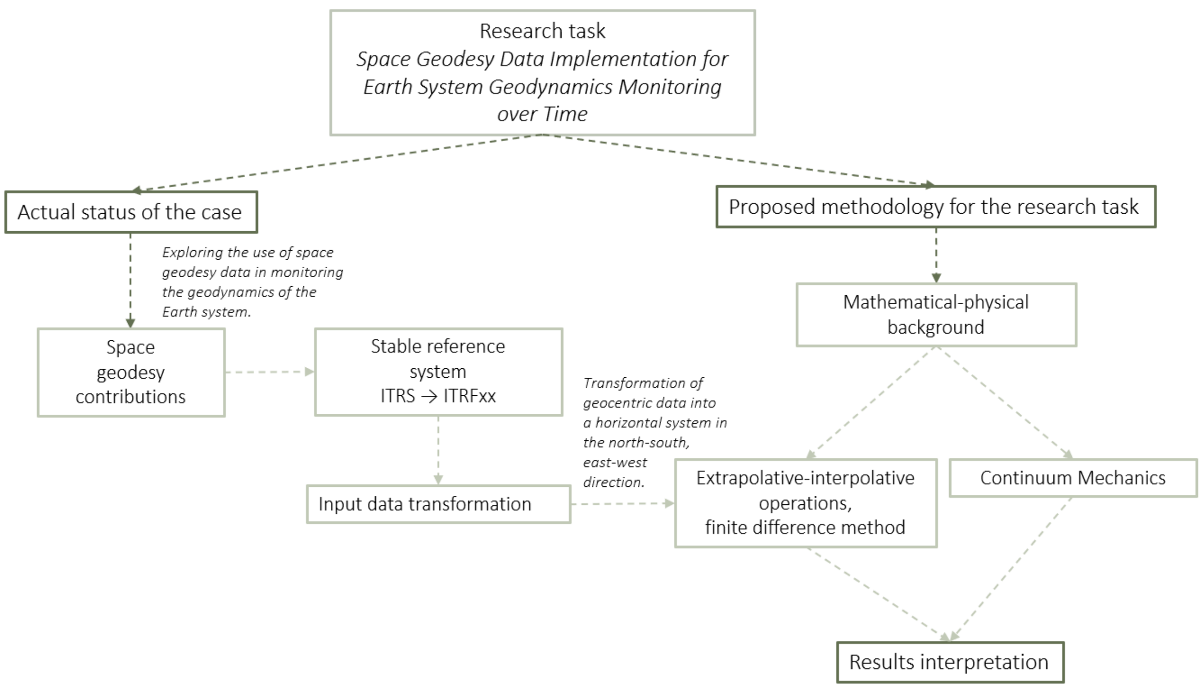

Fig. 3: The research task methodology design (Authors)

As it follows from the design of the task processing methodology (Figure 3), it is necessary to design and define the correct mathematical and physical background into the essence of which the data provided by space geodesy methods are implemented.

In the context of the implementation of the space geodesy data into the calculations and the chosen methodology for the interpretation of horizontal deformations, the basic condition is the definition of the computational environment, i.e. the selected study site, defined as a polygon with minimum and maximum values of latitude and longitude, must represent a continuous deformation field with certain strain directions. In this case, the condition is to define the earth as a continuum in which the deformation analyses will be carried out. Continuum mechanics allows to describe the changes or deformations of the continuum under study by a deformation tensor, from which it is then possible to extract information about the direction and magnitude of dilation or compression at the point.

The data provided by IERS (International Earth Rotation and Reference System Service) in the form of *.SSC and *.SINEX files for each ITRS realization - International Terrestrial Reference Frame (ITRFxx, where xx represents epochs from 1996 - 2020) represent the input information for the calculation of the strain tensors. Since the observation stations of the individual space geodesy techniques do not represent a network with a regular distribution of stations, and at the same time the density of the networks of the individual space geodesy techniques is not the same, a necessary step before the implementation of space geodesy data in continuum mechanics for the calculation of strain tensors is the determination of extrapolation and interpolation conditions. However, before the actual extrapolation and interpolation step, it is necessary to modify the input data so that the horizontal deformations of the Earth's surface can be observed and interpreted.

2.1 Data transformation

The primary input database are represented by the data provided from current International terrestrial reference frame 2020 (ITRF2020). The primary selection of the data depends on the choice of the investigated site and its extent - the object of investigation of horizontal deformation can be the primary or secondary tectonic plate, or only a part if it is necessary to focus on a small tectonically active part due to the presence of extreme geodynamic processes.

The data necessary for the calculation are derived from the SINEX files, especially *.SSC (SINEX Stream Compressed) and *.SNX files provided by IERS for the individual realizations of the ITRS at epoch 2020 (ITRF20) [30]:

- Geocentric coordinates X, Y, Z [m] of permanent observation stations and related standard deviations (STD) m_x, m_y, m_z [m];
- Velocities, i.e. the translation related to each axes per year v_x, v_y, v_z [m/y] and related standard deviations (STD) $m(v_x)$, $m(v_y)$, $m(v_z)$ [m].

Since the input data provided by IERS in the form of *.SSC and *.SNX files define the position of the observing stations relative to the Earth's geocenter using the geocentric coordinates X, Y, Z and their changes relative to the individual ITRS axe s in time v_x,v_y,v_z [m/yr], it is necessary to transform these data in order to monitor the horizontal deformations of the Earth's surface for selected observing locations, i.e. to interpret the deformation analysis in the direction of geographical coordinates (in the North-South, East-West direction).

The input data had to undergo a selective operation. The tested parameter was the STD of input attributes and the boundary criterium was set to ± 2 cm as the positioning accuracy of space geodesy methods is orders of magnitude higher. However, the selection had to be investigated beforehand in relation to local tectonic phenomena. Observing stations that showed large mean errors in X, Y, Z directions had to be assessed for the possible influence of tectonic phenomena that could affect the accuracy of positioning. In case of confirmation of the presence and possible influence of such phenomena (earthquakes, tsunamis, tectonic faults, etc.), permanent stations even with a root-mean-square spatial error (RMSSE) larger than ± 2 cm were further used in the calculations and analyses. From a certain point of view, the analysis of such discrete anomalous stations also presents the possibility of linking tectonic phenomena to research methodology and interpretation. However, permanent stations which horizontal or vertical shift report greater value than 0.3 m/yr, were not applied into consequent calculations.

The approach to transform ITRS coordinates from geocentric X, Y, Z to geodetic φ, λ [°] and to transform velocities related to the axes X, Y, Z into their expression related to the direction corresponding to latitude and longitude, i.e. velocities in the direction S-N, W-E is based on the transformation of rotation angle of Eulerian type and its principle is described bellow.

A rotation angle transformation of Eulerian type is employed to convert the components of changes - velocities in the time coordinate. This transformation involves using Z and Y transformation matrices to rotate from one system to another. Equation (1) is used to transform the motion vectors of observation and collocation stations relative to the terrestrial system, allowing for the consideration of only the horizontal motion of tectonic plates and observed sites, respectively.

$$\begin{pmatrix} v_n \\ v_e \\ v_h \end{pmatrix} = Y(90° - \varphi).Z(\lambda).\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} \text{[31,32]}, \tag{1}$$

where:

$v_{n/e/h}$ – velocities referring to the direction South-North/East-West/Up,

Y, resp. *Z* – euler angle transformation matrices with arguments 90°- φ, resp. λ, in the form according [33]:

$v_{x/y/z}$ – velocities referring to the direction of the geocentric coordinate system with axes X, Y, Z.

The transformation output is the displacement vectors of the observation stations in the N-S and E-W directions, making it possible to detect and analyse horizontal deformations of the Earth's surface. It is necessary to apply the last correction, namely to rotate the shifts for the N-S direction to define a shift in the direction of increasing latitude.

In order to fully unify the data, it is necessary to transform the geocentric coordinates of the permanent observation stations into geodetic coordinates. By analogy, latitude refers to displacements and transformations in the N-S direction and longitude in the E-W direction. The *.SNX files contain the values of the geographic coordinates of the observing stations, but in their approximate value (APPROX_LON and APPROX_LAT, respectively), therefore, despite the values of the geodetic coordinates given, these coordinates were calculated from the geocentric X, Y, Z coordinates, based on the GRS80 ellipsoid parameters and the well-known conversion relations and iterations for latitude [34,35].

2.2 Mathematical extrapolative-interpolative operations

The condition for monitoring the horizontal deformation of tectonic plates is to define the observed site (computational environment) as a continuous deformation field with certain strain directions, i.e. the Earth is defined as a continuum. Due to the uneven distribution of observation stations of different space geodesy techniques and the task of interpreting the horizontal deformation of a tectonic plate (or part of it) indirectly on the basis of the change of the position of the observation stations in time, it is necessary to define the values of displacements mathematically and consequently deformation indicators in locations without the presence of an observation station, based on interpolation conditions in a suitably chosen step (Figure 4).

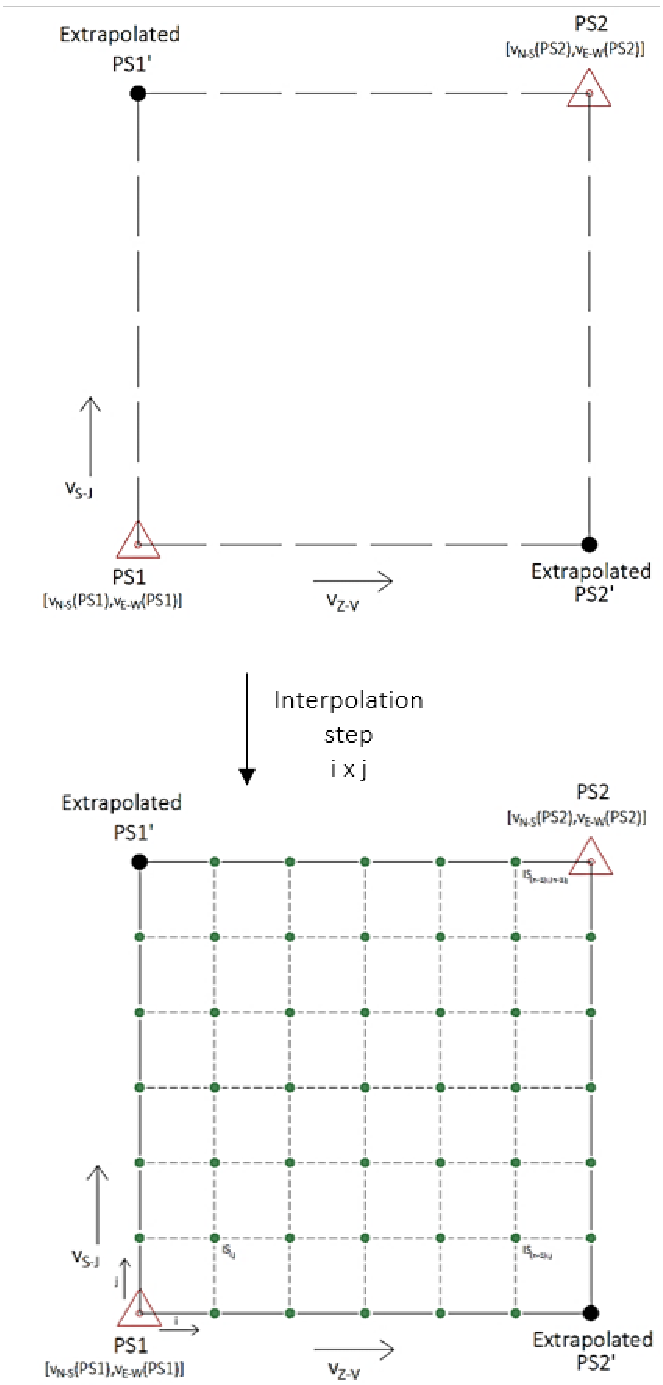

Fig. 4: Extrapolation and interpolation step (Authors)

The linear extrapolation method is based on the least squares approximation of the gradient on the convex boundary. The linear extrapolation method was chosen to extrapolate points forming a regular grid with known data for the position of the grid corners and their displacement values. Linear extrapolation involves forming a tangent at the boundary of the known data and extending this tangent beyond this boundary.

Principle: If the points (x_{k-1}, y_{k-1}) and (x_k, y_k) represent two point data in the vicinity of the extrapolated point x', the linear extrapolation is given by the function:

$$y(x') = y_{k-1} + \frac{x' - x_{k-1}}{x_k - x_{k-1}}(y_k - y_{k-1}), \quad (2)$$

This approach created a continuous space to carry out the chosen interpolation method in a predefined step. The output file from the extrapolation calculation was tested for different types of

interpolation. When linear interpolation is applied, the problem of second derivative calculations arises. Since the mathematical relationships of linear interpolation imply that the course between two points is linearized, and thus forms a straight line. The goal of the interpretation is to calculate tensors and hence second derivatives of displacements. The second derivative of a point lying on the line is equal to zero. The calculation using linear interpolation negatively distorts the values of the results of the displacement tensors, so it is necessary to look for another way of solving it. Based on testing, primary modelling and visualization of the interpolation results, the natural neighbour interpolation method was chosen since the results indicate a smoother approximation of the underlying "true" function.
$G(x) = \sum_{i=1}^{n} w_i(x) f(x_i)$ [36,37]., (3)where:
w_i – predefined weighs based on input data STDs and the relative distance of neighbouring points resulting from the interpolation step,
G(x) – the estimated unknown x,
$f(x_i)$ – the known data for x_i.

The interpolation results in points defined by geodetic geographic coordinates (depending on the selected interpolation step/grid, i.e. 1°) along with displacement values in the N-S, E-W direction. All mathematic operations were performed using Matlab and corresponding scritps.

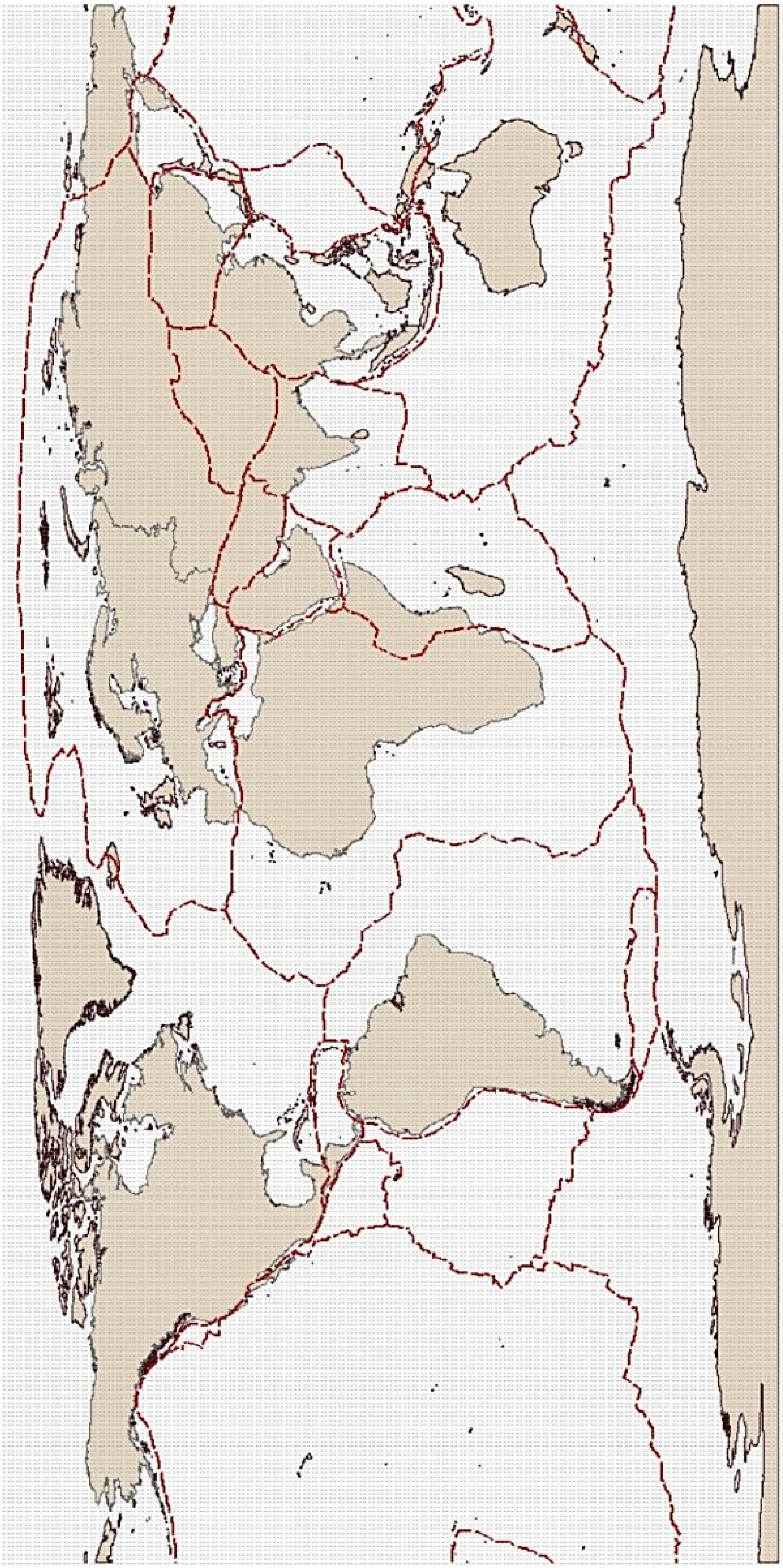

Fig. 5: Result of extrapolation-interpolation operations (red points in 1° step represent the result of extrapolation and interpolation); grey lines - continent boundaries and red line - tectonic plate boundary (Authors). Tectonic plates' boundaries [38]

Thus, the mathematically densified continuous field of observational permanent and collocated stations (64 800 points) represents a computational environment for performing deformation analyses with the assumption that the defined environment is a continuous deformation field with certain strain directions (Figure 5).

2.2 Physical background

The condition for monitoring horizontal deformation of tectonic plates is to define the observed site (computational environment) as continuous deformation field with certain stress directions. In the study of the deformation of the Earth's body caused by the gravitational pull of the Moon and Sun, or in the study of seismic waves, the Earth is usually treated as a continuum [39,40]. Based on continuum mechanics, continuum changes/deformations can be described by strain tensors. To approximate the changes in the position of a small neighbourhood of point P (an infinite number of points in this neighbourhood), it is sufficient to know a finite number of quantities (three components of the displacement vector of point P and nine components of the derivatives) → the displacement of the whole body (if it has a finite volume) can be approximately described by a finite number of quantities if this body is divided into a finite number of small parts. By transferring continuum mechanics to the problem at hand, space geodesy data can be applied to deformation tensor calculations to study horizontal deformations of the Earth's surface. It is necessary to pre-define these conditions:

- Displacement vector d with components u_x, u_y from the evaluation of time series coordinates of space geodesy methods, where u_x is the displacement in the north-south direction and uy is the displacement in the transverse direction;
- Continuous deformation field with certain stress directions;
- Choices of the local coordinate system (x, y) on the reference body (ellipsoid or sphere) at the investigated point P with geographical coordinates φ, λ were dφ = dx and dλcosφ = dy.

The displacement gradient E = grad(d) has the following form:

$$E = \begin{pmatrix} \epsilon_{11} & \epsilon_{12} \\ \epsilon_{21} & \epsilon_{22} \end{pmatrix} = grad(d) = \begin{pmatrix} \frac{\partial u_x}{\partial_x} & \frac{\partial u_x}{\partial_y} \\ \frac{\partial u_y}{\partial_x} & \frac{\partial u_y}{\partial_y} \end{pmatrix} \text{[41]}, \tag{4}$$

where:
E – the strain tensor,
d – the displacement vector,
u_x, u_y – components of the displacement vector.

$$d = Ex + t, \tag{5}$$

where:
E – the strain tensor,
d – the displacement vector,
x – the coordinate vector,
t – the translation vector.

As may be seen from equation (4), the third dimension (vertical component) is omitted and (4) is simplified to deal with the horizontal movements and deformations. This approach was chosen with the intention of tracking horizontal displacements and deformations, and the method of approach is derived from previous research carried out by Prof. Kostelecky [41].

The strain tensor E is composed of a symmetric strain tensor e and an antisymmetric strain tensor Ω, where in subsequent calculations only the symmetric part of the total strain tensor is applied which includes the parameters such as dilatation or compression.

$$e = \begin{pmatrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{pmatrix} = \begin{pmatrix} \epsilon_{11} & \frac{\epsilon_{12}+\epsilon_{21}}{2} \\ \frac{\epsilon_{12}+\epsilon_{21}}{2} & \epsilon_{22} \end{pmatrix}, \tag{6}$$

The components of tensor e in (6) define the deformation parameters, especially the compression γ and dilatation Δ.

$$\Delta = e_{11} + e_{22} \quad (7)$$
$$\gamma = e_{11} - e_{22} \quad (8)$$

Calculating the individual components of the strain tensors follows the principles of continuum mechanics and the following mathematical operations. Since from the input data and the transformations and extrapolation-interpolation steps applied so far, the components of displacements in the N-S, E-W directions are available; the next step is the formation of the deformation tensors and the analysis of the individual members of the matrix notation of the tensors. The principle is to find derivatives of the known displacement values (4). The problem is that the deformation vectors are only available as numerical values at discrete locations on the Earth's surface rather than in continuous analytical functions. The partial derivatives are, in this case, approximated using the first-order finite difference stencil. Implementing this technique, the partial derivatives of displacement and the deformation tensor with principal deformation directions are calculated. The first-order stencil can be concretized and simplified in the form of:

$$\left.\frac{\partial u}{\partial x}\right|_{x = x_n} = \frac{u_{n+1} - u_{n-1}}{2h}, \quad (9)$$

where *h* represents the horizontal distance between neighbouring points.

Equation (9) describes the search for deformation tensor components within a continuous environment. It is an approach where the resulting values of the partial derivatives of the displacements in the N-S and E-W directions, respectively, are sought within the natural neighbourhood of the adjacent partial derivatives of the neighbouring displacements defined for the neighbouring points. The individual components of the strain tensor allow the calculation of the values and direction of the applied strain forces. In the context of the study of horizontal deformation of the Earth's surface, these vectors will represent dilation and compression. Based on calculations with the application of the finite difference principle, the values of the partial derivatives of the shifts are available $\frac{\partial u_x}{\partial x}, \frac{\partial u_y}{\partial y}$ and $\frac{\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y}}{2}$. It is the mixed component that is then used to determine the type of vector interaction (dilation/compression) and their magnitude.

3 Results

The resulting interpretation was related to the chosen observed locality. The choice of this locality was based on the pre-defined terms and conditions mentioned above (permanent observation stations in the locality, presence of geodynamics and tectonic phenomena etc.). According to this, the region of Balkan peninsula was selected to be monitored using the implemented space geodesy data into designed methodology.

3.1 Study area overview

The site can be characterized as a tectonically active area with frequent occurrences of earthquakes and volcanic activity (Figure 6), which are the result of the interaction of the tectonic plates whose boundaries lie within the site. In the southern part of the defined site is the boundary between the Eurasian and African tectonic plates, which is defined as convergent on the basis of their interaction. Over millions of years, the African plate has been gradually moving northwards under the Eurasian plate. In addition to these primary tectonic plates, the so-called subsidiary tectonic plates of the Eurasian tectonic plate - the Aegean Sea Plate and the Anatolian Plate - are located in the locality.

The convergent boundary between the African and Aegean plates is the Hellenic subduction zone. At this point, the oceanic crust of the African Plate dips and subducts beneath the Aegean Sea in a N-NE direction, with the southernmost part located beneath part of the Mediterranean Ridge. The southern part of this zone is the shallowest and increases towards the north. The impact of the subduction of the African plate was the formation of a volcanic arc - the South Aegean Volcanic Arc. In general, Greece is one of the most frequently deformed parts of Europe, due to earthquakes exceeding magnitude 8.0. The complexity of the Hellenic lithospheric system (the Hellenic Arc, the trench system and the back arc of the Aegean microplate) is a consequence of the N-S retreat of the subducting African plate along the Hellenic Subduction Zone (HSZ) and the subsequent accretion of its surface crustal sediments, resulting in the closure of the oceanic regions of the Tethys [42].

Extensive research using geological, seismological and geodetic approaches has explained the geodynamics of the Hellenic lithosphere as the result of the northward advance of the African and Ionian crust north of the Cretaceous, forced by the subduction of the Tethys oceanic plate beneath the Aegean microcontinent, which led to the return of the subduction zone. Overall, the regional kinematics are dominated by SW spreading, which is explained as the result of three fundamental processes related to convergence between the African, Aegean and Anatolian plates. Through this region, convergence of the African and Eurasian plates occurs in the range of 25-40 mm/yr [43]. The second process relates to the westward advance of the Anatolian plate into the Aegean Sea due to the northward pressure of the Arabian plate. The third process is the extension of the overlying plate in the back-arc region. According to the results of scientific studies available so far, the average horizontal velocity of the Earth system in the region of Greece is 10 mm/year and in the Hellenic Arc region it is 40 mm/year, which defines an active boundary between the Aegean and African lithospheres characterized by a 1300 km long trench cluster [44]. The western Hellenic subduction zone extends along the west coast of Greece (from Corfu to western Crete), where convergence related to the subduction of several ocean basins and continental parts is confirmed from the Jurassic/Cretaceous to the present.

Based on a study using surface wave tomography data by [45], the shear waves of the lower Hellenic lithosphere were determined, whereby phase velocity dispersion was investigated by analyzing several thousand teleseismic Rayleigh waves in the fundamental mode using a cross-correlation scheme that accounts for multipath/back-scattering effects. By analyzing such input data, the horizontal deformation of the Earth's surface in the region of Greece was visualized (Figure 6).

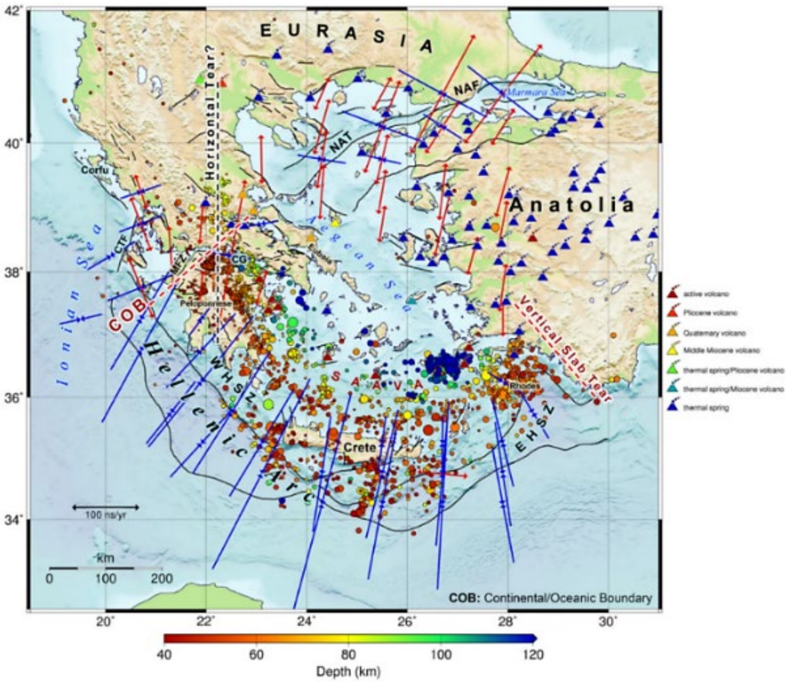

Fig. 6: Horizontal deformation of the Earth's surface (dilation/compression) from teleseismic Rayleigh-wave tomography data showing volcanic regions [45]

The observed locality is defined as a polygon with following boundaries: φ = <34°N; 42°N> and λ= <19°E; 35°E>. The motion of the lithospheric plates can be described in a mediated way by the change in the position of permanent observation stations, thus defining the motion of the Eurasian Plate and its individual parts. The southern to southeastern boundary of the Eurasian Plate is defined by convergent boundaries. The boundaries of the southern microplates of the Eurasian Plate (Aegean and Anatolian) form a transformed kind of boundary with the primary plate. The motion of the primary Eurasian plate is towards the NE, which is confirmed by the graphical representations of the motion of the observation stations for the whole world from the calculations (Figure 7).

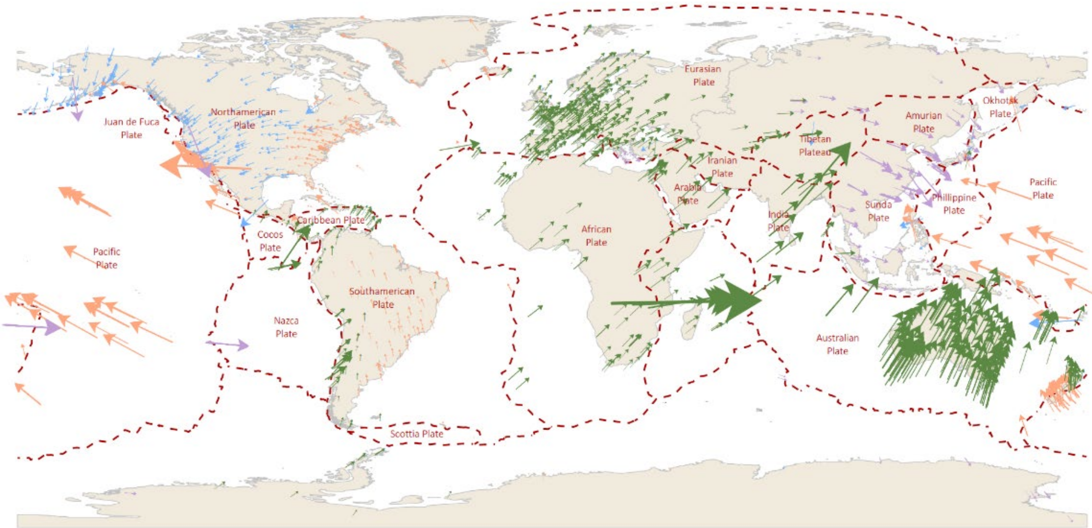

Fig. 7: Relative horizontal shifts of permanent observation space geodesy stations (ITRF2020) worldwide with emphasis on illustration of the mediated movement of tectonic plates (Authors). Tectonic plates boundaries source [38]

Based on the results shown graphically in Figures 7 and 8, the conventional motion of the Eurasian Plate towards the NE can be confirmed. The detail in Figure 8 shows the displacements of the permanent stations in the selected study area. At the SE boundary of the Eurasian and African tectonic plates (the vicinity of the island of Cyprus), it is possible to observe not the NE motion of the Eurasian plate, but motion towards the SE. The reason for this anomalous movement is the fact that there is a microplate of the Eurasian Plate, namely the Aegean Plate, in this part. This tectonic microplate carries out different movement. Very frequent and strong earthquakes in the area of Balkan peninsula declares the ongoing Earth-endogen processes in the background. As mentioned above, the Hellenic subduction zone represents the convergent boundary between the African and Aegean plates. In relation to the Eurasian tectonic plate, the boundary with the Aegean plate is defined as a transformed boundary. Creation of this subduction zone resulted in the the formation of a volcanic arc - the South Aegean Volcanic Arch. The results of primary analysis, devoted to the assessment of the movement of tectonic plates mediated by the movement of permanent stations within the epoch, confirms:

- the conventional movement of the Eurasian plate to NE exceeding 2 cm/year as mentioned for example in [46];
- different behaviour of the Aegean microplate in the terms of its trend of movement;
- the movement of the Aegean microplate to SE at rate 1 cm/year as mentioned in [44];
- localities with the higher risk of the tectonic activity occurrence in the region of Balkan peninsula on the boundary with the African tectonic plate.

Fig. 8: Horizontal shifts of permanent observation space geodesy stations (ITRF2020) in the locality of Balkan peninsula (Authors), Tectonic plates boundaries source [38]

3.2 The interpretation of the Earth's crust horizontal deformations

The horizontal movement of the pre-eliminated permanent observation stations were used in the horizontal deformation analysis methodology, described in the Methods and methodology section. Different approach to horizontal deformation of the Earth crust interpretation was chosen:

• The graphical illustration of the horizontal deformation represented by the volume change dV (mass loss/accumulation). The interpretation using the dV parameter represents the overall deformation at the site, i.e. without the distinguishing of the deformation character (compression or dilatation). This approach was enabled due to the extrapolative-interpolative operation that densified the computational environment. The regular point grid may be easily converted into raster representation and the dV parameter is consequently expressed in % and by hypsography representation. The mass loss, i.e. localities/tectonic plates' boundaries were the horizontal deformation in the form of dilatation occur (divergent boundaries), is represented by blue colour. On the contrary, the mass accumulation, i.e. localities/tectonic plates' boundaries were the horizontal deformation in the form of compression occur (convergent boundaries), is represented by red colour (Figure 9).

• The graphical illustration of the horizontal deformation represented by the deformation tensors. The localities/tectonic plates' boundaries were the horizontal deformation in the form of dilatation occur (divergent boundaries), are represented by blue colour. On the contrary, the localities/tectonic plates' boundaries were the horizontal deformation in the form of compression occur (convergent boundaries), are represented by red colour (Figure 10).

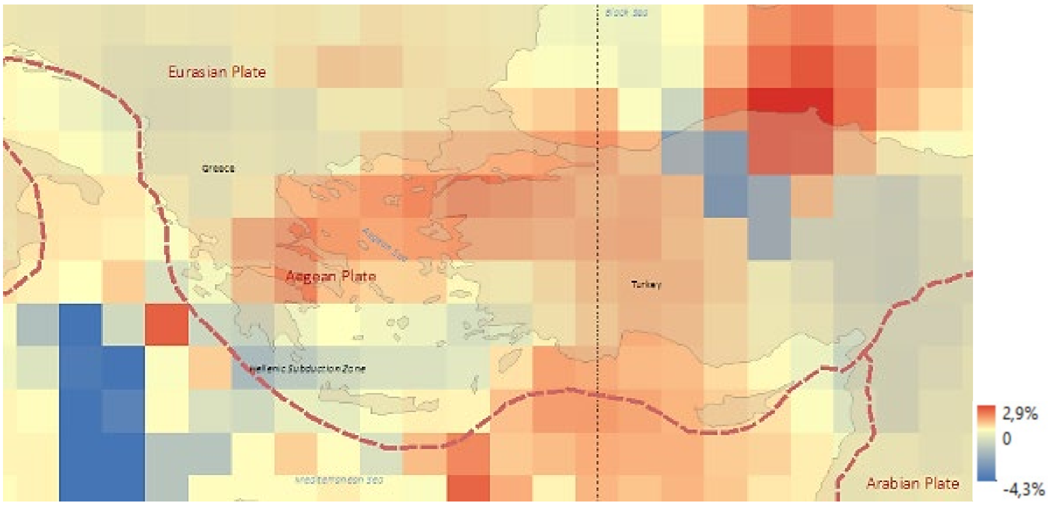

Fig. 9: The graphical illustration of the horizontal deformation represented by the volume change dV (mass loss - blue/accumulation - red) from the ITRF2020 data (Authors), Tectonic plates boundaries source [38]

Based on the computation methodology and according to the Figure 9, the presence of dilatation in the area of the Hellenic subduction zone confirms the contradictory trend in movement of the Aegean plate in relation to the Eurasian plate.

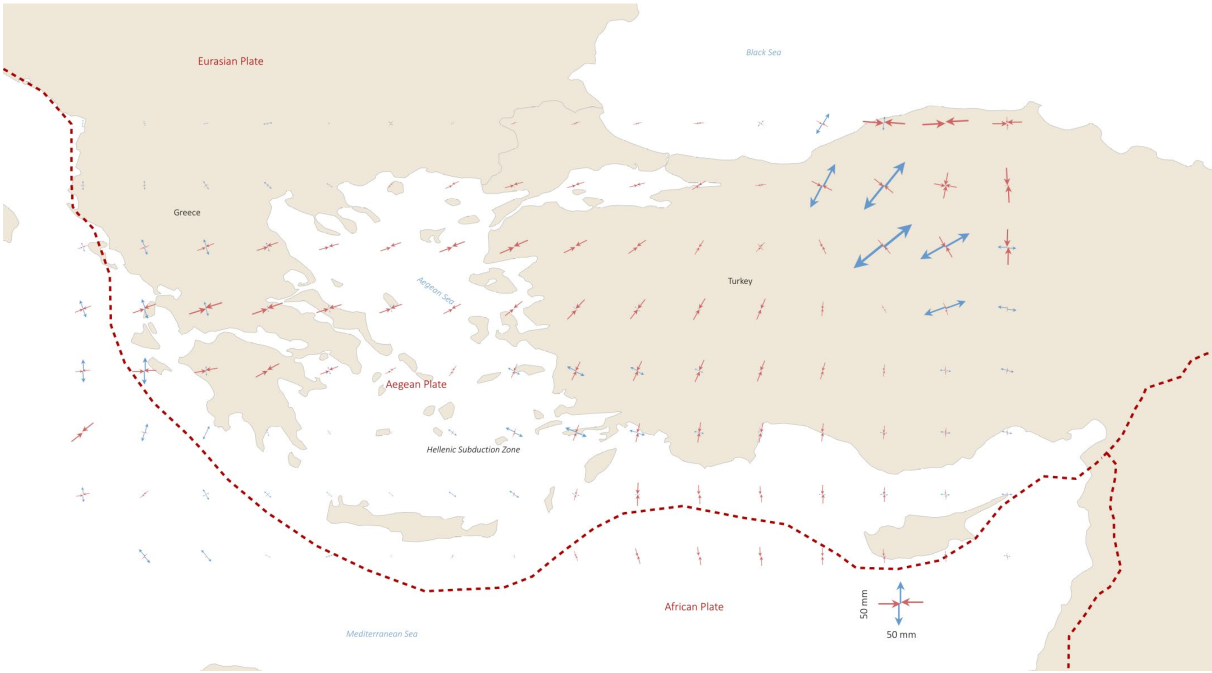

Fig. 10: The graphical illustration of the horizontal deformation represented by the deformation tensors (dilatation - blue/compression - red) from the ITRF2020 data (Authors), Tectonic plates boundaries source [38]

By interpreting the Figure 10, the prevailing dilation may be observed in the Hellenic subduction zone confirming the above mentioned claims. The deformation tensors take on a value of up to 1 cm/year in the area of Balkan peninsula. More significant dilatations may be seen in the eastern part of Turkey, were the boundary between the Anatolian, Arabian and Iranian plates is. This locality is also very well-known for the occurrence of the strong and devastating earthquakes due to the presence of the tectonic faults.

4 Conclusion

Space geodesy products and data are applicable in various fields not only in science but also in social life. With the development, improvement and refinement of procedures for defining a stable geodetic framework and determining the spatial position of points on the Earth's surface with millimetre accuracy, space geodesy techniques have become an indispensable source of information in interdisciplinary research with the requirement for very accurate geolocation in a homogeneous system. Tracking of the Earth system - its variability and dynamics, allows to understand significantly better the functioning of the Earth system and to reveal the reasons for the occurrence of various dynamic manifestations. Dynamic phenomena occurring under or on the Earth's surface can have a significant impact not only on the Earth system itself in the form of deformations and displacements, but also on the environment and the safety or quality of human life.

The presented study implements the ITRF2020 data of the space geodesy techniques VLBI, SLR, DORIS and GNSS into the individual mathematical and physical calculations and steps, thus forming the methodology for the geodynamics monitoring and interpreting only from the space geodesy data. Set methodology – the choice of the input data and their processing within mathematical operations with the physical background of the continuum mechanics theory, provided the fundamental approach to possible interpretation and visualization of the results. Individual operations intended to ensure the objective and a credible approach to prove the application of the data provided by the space geodesy techniques within the geodynamics. The research task's results confirm and support the outputs and statements provided by other geodynamic-related fields of research (seismic, geological approach etc.).

The dynamics of the Earth system was considered from two perspectives, namely translational (movement of lithospheric plates) and deformational (interaction of lithospheric plates). Based on the processing of the research task and an emphasis on tracking changes in the Eurasian and Aegean lithospheric plate, the conventional motion of the Eurasian lithospheric plate towards the Northeast was confirmed, and the average value of NE displacement is 2.69 cm, i.e., the rate of movement of the Eurasian lithospheric plate is 2.69 cm per year.

The southeastern part of Europe, especially around the Balkan Peninsula, is known for frequent tectonic activity in the form of earthquakes that reach a magnitude of over 5.0 (so far the strongest in the last 20 years - an earthquake in the Aegean Sea near the island of Samos - the western coast of the Balkan Peninsula with a magnitude of 7.0).

Tectonic activity in the form of earthquakes in this area of Europe is a direct impact of the active movement of lithospheric plates - the main Eurasian plate and its microplate, the Aegean plate. Based on the results of the task, it is possible to observe a diametrically different movement of SE Europe in the area of the Balkan Peninsula compared to the movement of the main Eurasian tectonic plate. Observing stations in this area show movement to the south to southeast, while greater movement can be observed at observation stations south of the Balkan Peninsula. The speed of movement takes on a value of up to 2.27 cm/year towards the southeast. The southern part of the Aegean microplate is also known as the Hellenic subduction zone, which is the meeting point of the two main tectonic plates - Eurasian and African, while the subduction of the African plate under the Eurasian plate occurs due to the movement of the African plate towards the north. As the Eurasian plate is moving in a northeasterly direction at the same time, the boundary between the African and Eurasian plates is defined as divergent. The anomalous movement of the Aegean microplate results in the emergence of appreciable tectonic activity in the region of the Balkan Peninsula.

The deformation analysis resulting from the research findings confirms the dynamics of the Earth's system in the studied area. Based on the calculations, it was possible to visualize the deformation of the Earth's system using graphical representations of the percentage volumetric change. Raster analysis allowed for a graphical representation of the decrease or increase in volumetric mass in various parts of the studied area. The percentage decrease or increase in volumetric mass corresponds to the deformation tensor composed of the components of compression and dilation. The graphical interpretation of the results in the form of deformation tensors makes it possible to observe the nature of movement in different parts of the studied area, whether it involves mutual convergence—compression (increase in volumetric mass) or, conversely, divergence—dilation (decrease in volumetric mass). The results indicate a predominant compression in the continental part of the Balkan Peninsula, with an average value of 4.7 cm, while dilation prevails over compression in the Aegean Sea on the western coast of the Balkan Peninsula, reaching up to 3.1 cm. The collision of lithospheric plate movements with opposite motion characteristics creates conditions for tectonic activity, which in this area manifests itself primarily in the form of earthquakes.

There is significant potential to elevate the methodology to a more advanced level. The vast amount of spatial and precise data provided by space geodesy techniques, which continuously monitor and determine the positions of permanent stations as well as their changes over time, can serve as an invaluable foundation for developing a comprehensive Earth-system model. By continually updating this model with data inputs through the application of neural networks, and by incorporating information from various other geoscience disciplines, it would be possible to create a dynamic, real-time model. Such a model would not only offer a deeper understanding of Earth's processes but also have the capability to predict the occurrence of natural disasters with greater accuracy, potentially improving early warning systems and disaster preparedness efforts on a global scale.

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