Cosmic Geodesy Contribution to Geodynamics Monitoring

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Abstract. The cosmic geodesy provides methods and ways of various data acquisition. The collected data may be used for research, calculations and analysis in different fields of interest. According to the reliability and redundancy of data provided by cosmic geodesy methods, it is possible to contribute to the geodynamics monitoring. The geodynamics monitoring enables the tectonic plates movement tracking and predicts the movements which may result in disasters. Applying data provided by cosmic geodesy methods in the form of permanent observation station positions and their changes in time, in calculations, whose physical nature is based on the continuum mechanics, makes possible to monitor the direction, locality and size of visualised deformation tensors.

1. Introduction

The Earth presents a complex system which was formed as a result of a long-term interaction of various actions. However, the process of Earth forming still goes on and the Earth surface is deformed due to the movement of tectonic plates. Geodynamics is an interdisciplinary scientific field, which applies the outputs of many fields, not only geo-fields, for the research purposes. The ongoing processes, which form the Earth’s surface, are modelled using the data from geology, geophysics, hydrology, seismology, geodesy, etc.

The requirement of tectonic plates’ movement tracking and Earth’s surface deformation monitoring is necessary. The possibility of prediction of upcoming deformation actions enables to prevent or reduce the negative consequences.

Cosmic geodesy provides the data, related to the position determination, with high precision and reliability. These data are acquired in different ways in relation to the permanent observation station type. The permanent observation stations differ one from another according to the used cosmic geodesy method which influences the way and form of collected data. GNSS, SLR, VLBI and DORIS belong to the mentioned cosmic geodesy data. Each of the mentioned cosmic geodesy data is based on different physical phenomena but all of them provide position determining of the permanent observation and collocation stations.
The permanent observation stations’ positions are determined continuously in time and it is possible to notice their changes in position after a selected time period. According to this, the calculations and analyses related to the Earth surface movement may be done and interpreted. The purpose of this research is to prove the cosmic geodesy contribution to geodynamics monitoring by applying the continuum mechanics theory and deformation tensor calculations and consequent visualization.

2. Cosmic Geodesy Contribution to ITRF Genesis
The permanent observation stations and their collocation stations are located worldwide and create a network with a different density in relation to the locality. In the territories of tectonic plated interface, where the earthquakes, tsunamis, volcanic and other tectonic activities occur, the density of permanent stations is much larger. In these localities, number of collocation stations are related to the permanent observation stations, which determine the position of the main permanent observation station but with a different ID. These stations permanently acquire data from the satellites, quasars or from other sources depending on the cosmic geodesy method, and the data redundancy enables the reliable calculations and interpretations.

The data provided by the permanent stations are related to a pre-defined coordinate system and its reference frame in accordance to ensure the homogeneity of the data. All already mentioned cosmic geodesy methods contribute to the International Terrestrial Reference Frame (ITRF) genesis. ITRF foundation is based on the individual SSC reduction (Set of Station Coordinates) related to common epoch by applying the models of tectonic plates movements and 7-parametres transformation of the individual solutions into the conventional system. New ITRF realization is based on the previous one.

The International Terrestrial Reference Frame 2014 (ITRF2014) presents the current realization of International Terrestrial Reference System [1]. In relation to this realization, the position of the permanent observation and collocation stations are determined by the cosmic geodesy methods in the form of geocentric coordinates. The stations’ positions in the time series and Earth orientation parameters provided by the cosmic geodesy methods belong to the input data, used by the ITRF2014.

The ITRF2014 origin is defined by the no-translation parameters in the epoch 2010.0 from the SLR solutions. The scale definition is acquired according to the average solutions from VLBI and SLR and orientation is described as NNR (No Net Rotation) toward the previous realization ITRF 2008 [2].

The ITRF genesis based on the cosmic geodesy methods presents the first cosmic geodesy contribution to be applied in consequent cosmic geodesy contribution – geodynamics monitoring.
According to Figure 1, it is possible to see that the density of the network is not equable, as mentioned above. In the territories of tectonic plates interface and interactions, the network density is much larger.

Other data, besides the stations’ position, provided by ITRF2014, which create the basis for the tectonic plates’ movement calculations, tracking and consequent visualization, are presented by the linear time variances in the stations’ position called velocities and the corresponding mean errors. These data are the basis for the deformation tensors calculations and consequent visualization and interpretations [3].

3. The Earth as a Continuum for Geodynamics monitoring
The uneven distribution of permanent observation and collocation ITRF2014 stations forces the interpolation to be applied in upcoming calculations. The pre-set condition of interpolation application determines the Earth to be considered a continuum, i.e. the environment with the continuous mass distribution without any discrete zones.

Within the studies of the Earth deformation caused by the attractive actions of the Moon and Sun or within the studies of seismic waves, the theory of continuum mechanics is applied and the Earth is considered a continuum.

Under the influence of the acting forces, the real solids are more or less deformed and the change in their shape and volume occurs. Determining the solid deformation is based on comparing its current condition with its previous or reference condition which is set as initial [4, 5].

In order to calculate the deformation tensors, it is necessary to define the grid size and radius of interpolation. The interpolation assumes that the environment, where the interpolation is applied, is continuous before the interpolation and also after the interpolation. According to the choice of appropriate interpolation conditions, it is possible to monitor the horizontal deformations in the areas with sparse permanent stations network.
Development of the outer space including extraction of mineral resources becomes a widely discussed issue [6].

4. Calculation Methodology and Interpretations of Deformation Tensors

Within the horizontal deformations studies related to the Earth surface deformations, it is possible to take two different approaches:

- repeated (epoch) measurements in terrestrial geodetic local network,
- continual measurements in the permanent observation stations’ network

Both of the mentioned approaches use the spherical coordinates $\varphi, \lambda$ [$^\circ$] and their linear time-variances of the permanent stations as the input data. The results are invariants – horizontal deformation tensors illustrated in the regular interpolated grid.

The calculations’ physical principle is based on the theory of continuum mechanics and the observed locality is considered a continuous deformation field. The deformation tensor is defined as a gradient $E$ of translation $d$. The translation vector $d$ consists of components $u_x$ and $u_y$ representing the movement in the direction north – south and in the direction perpendicular to the first component. The deformation tensor contains two elements – the symmetric and non-symmetric deformation tensor, whereas for the deformation interpretation only the symmetrical part was necessary [7].

The deformation tensor consists of the positive component (dilatation) and negative component (compression). The graphical illustration of the deformation tensor is displayed in Figure 2. To avoid misunderstandings, this graphical illustration (colour) of the deformation tensor is used in all Figures (Figures 4, 5, 8).

The deformation tensors represent the graphical illustration of the lithospheric plates’ movements. According to the input data (coordinates of the permanent observation stations and their velocities) used in the calculations, the deformation tensors are visualised and consequently interpreted. In order to ensure the clarity and informative values, the localities of Europe and Japanese Islands were chosen as the examined areas.

In order to elucidate the deformation tensors’ meaning and location, it is necessary to take into consideration the tectonic plates’ boundaries (see Figure 3).
Figure 3. The major and minor tectonic plates

The calculated and visualised deformation tensors provide the data and the idea of differences in the local velocities’ vectors which lead to the ideas of the current movements of Europe in general and also the partial movements within Europe. The deformation tensors calculated for the European territory are displayed in Figure 4.
The western, central and northern parts of Europe do not show large shifts or movements. More significant deformations, but still smaller than 1 mm/100 km/year, may be observed in the Netherlands, on the northern Norwegian coast and between Iceland and Faroe Islands. The compression occurs between Iceland and Faroe Islands and acquires values up to 2.7 mm/100 km/year. The Mid-Atlantic Ridge, known as Reykjanes Ridge, goes through Iceland and divides the Eurasian plate from the North American plate. In the territory of the Mid-Atlantic Ridge, the active Icelandic volcanos (i.e. Krafla) are located.
According to Figure 4, the largest deformations are observed in the south-east Europe, in the territory of Balkan Peninsula, Apennine Peninsula and Turkey. In this part of Europe, the lithospheric plates’ movements occur in the form of earthquakes and volcanic activities.

Near the Apennine Peninsula, the most significant deformations are located in Sicily, where the volcano Etna is situated. North of Sicily, the dilatation is larger than compression and south of Sicily, the compression is larger. The dilatation acquires value of 2.9 mm/ 100 km/ year and compression values of 4.2 mm/ 100 km/ year.

An order larger movements are observed in the Balkans and Turkey. The detailed illustration of deformation tensors in this area is displayed in Figure 5.

Figure 5. Balkan Peninsula and Turkey – deformation tensors

The dilatation is larger than the compression in the direction from western coast of Balkan Peninsula to Turkey. In Turkey, the more significant dilatation in the west smoothly changes into compression in the east. The compression is also larger in the territory of Aegean Sea and between the Apennine and Balkan Peninsula. The dilatation acquires value up to 15.6 mm/ 100 km/ year and compression up to 12.3 mm/ 100 km/ year.

The Anatolian plate and Aegean Sea Plate are located over Egypt at the northern end of the Mediterranean Sea and are considered the microplates of the Eurasian plate. In relation to the Eurasian plate, the Anatolian plate moves in the western direction and the Aegean Sea plate in the south-western direction. The boundary between the Aegean Sea plate and Eurasian plate is known as the Hellenic
subduction zone. On the plates’ interface, the dilatation and compression meet and this interaction results in earthquakes’ origin – in the western edge of the Aegean Sea plate, in the territory of Greece, many earthquakes occur.

The deformation tensors mentioned in the localities of Sicily, Turkey and Hellenic subduction zone are very significant and confirm the ongoing tectonic plates’ movements. This statement may be proven by following figures, which illustrate the localities characterised by the earthquakes and volcanic activities. The legend in Figure 6 refers to the size and magnitude of the earthquakes.

![Figure 6](image1)

**Figure 6.** Localities with a common occurrence of earthquakes in Europe [7]

![Figure 7](image2)

**Figure 7.** Volcanic areas in Europe (red – active, orange – potential active, yellow – inactive, blue – submarine) [8]

The Japanese Islands were chosen as the second examined area as they are located in the territory of many tectonic plates’ interactions. Many ITRF2014 permanent observation stations occur on these islands. The major part of Japanese observation stations has several collocation stations. These redundant observations enable reliable calculations of horizontal deformation tensors and consequent
interpretation in the end. The Japanese Islands are located in the eastern edge of the Eurasian tectonic plate and their eastern coast presents the boundary between the Eurasian plate and Philippine Sea plate. On the south-eastern boundary of the Eurasian plate, along the Nankai Through, the Philippine Sea plate sinks under the Amurian plate [9]. The Philippine Sea plate moves northwest in relation to Eurasian plate and sinks under Amurian and Okinawa plate at the speed of 55 mm/ year and 75 mm/ year. On the eastern boundary of the Philippine Sea plate, the North-American plate sinks.

The most significant deformations are observed in the central and northern parts of Honshu Island. In both of the mentioned parts, the interface of the dilatation and compression occur. In the central part, the dilatation acquires value up to 55.4 mm/ 100 km/ year and compression up to 62.6 mm/ 100 km/ year. The graphical illustration of deformation tensors in the territory of the Japanese Islands is displayed in Figure 8.

**Figure 8.** The Japanese Islands – deformation tensors
The deformation tensors’ placement confirms the frequent occurrence of earthquakes and tsunamis in the territory of Japanese Islands (Figure 9), for example, the Tohoku earthquake which had an enormous worldwide impact, especially due to the disturbance of the nuclear plants. According to the calculations based on the ITRF2014 data, the dilatation reaches values up to 70.7 mm/100 km/year and the compression up to 56.3 mm/100 km/year. Due to the compression and the pressure formations, the tsunami forms.

Figure 9. The Japanese Islands – the locations with the earthquakes occurrence (left) – the scale and legend is identical to the one in Figure 6.; and volcanic activities (right): red – active, orange – potential active, yellow – inactive, blue – submarine [8]

Beside the deformation tensor calculations, also another cosmic geodesy contribution to the geodynamics monitoring may be mentioned. The data from GRACE satellite mission (launched in 2002) showed the gravitational changes in the territory of Japanese Islands. The changes started several months before the mentioned Tohoku earthquake (M = 9.0). The satellite data together with the cosmic geodesy data may be applied in the Earth gravitation field research and present a significant contribution within the prediction of earthquakes, which cause the horizontal and also vertical deformations. (Figure 10)

Figure 10. Gravitational gradient around the area of Tohoku earthquake before, during and after the earthquake [10]
5. Conclusions

Cosmic geodesy methods enable very precise position determination of the selected point, represented by the permanent observation station. Whereas the position determining is performed by permanent observations, it is possible to monitor the change in station positions smoothly with time. These changes present the ITRF velocity parameters related to every permanent and collocation station.

According to the deformation tensors’ calculation and visualization, it is possible to examine and determine the locality and sense (dilatation/compression) of the deformations. Before the final interpretation of the deformation tensors based on their visualization, the localities characterized by the tsunami, earthquakes or volcanic activities, were supposed to be represented by significant deformation tensors. These predictions were consequently confirmed. The significant and the largest calculated and visualized deformation tensors occur in the territories of tectonic plate breaks – in the places of tectonic plates’ interaction, tectonic plates mutual movements along each other or towards each other (subduction) etc. This interaction leads to the pressure creation between the plates and the deformation processes commence.

The deformation tensor interpretations and visualization confirmed that the global coordinate systems (ITRF 2014), which provide precise data acquired by the cosmic geodesy methods, enable global and regional deformation studies. The results confirm that the horizontal deformations occur in the localities where the earthquakes or other tectonic activities have been monitored and are reasons of the Earth crust deformation.

Cosmic geodesy provides a significant contribution to the deformation research, interpretation and modelling. In conjunction with other research fields’ outputs, which include the data and information about Earth crust and geodynamic processes from the different points of view, it is possible to create the complex and detailed deformation models.

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References
[1] International Terrestrial Reference Frame [Online] 2021 [Accessed 2021-05-07]. Available online: http://itrf.ensg.ign.fr/general.php.
[2] M. Šnajdarová, and J. Kostelecký, “Motions and deformations of tectonic plates inferred from the ITRF 2005”, Acta Geodynamica at Geomaterialia, 2009. ISSN 1214-9705.
[3] Z. Altamimi, P. Rebischung, L. Métivier, and X. Collilieux, ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. Journal of Geophysical Research: Solid Earth. 121, 6109-6131, 2016. doi: 10.1002/2016JB013098. Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016JB013098.
[4] O. Novotný, Mechanika Kontinua. Matematicko-fyzikální fakulta Univerzity Karlovy v Praze. 1976 (in Czech).
[5] M. Brdička, L. Samek, and B. Sopko. Mechanika kontinua. Vyd. 3. rev. Academia. Praha. 2005. ISBN 80-200-1344-X (in Czech).
[6] A. Khairutdinov, Y. Tyulyaeva, C. Køngar-Syuryun, and A. Rybak. Extraction of minerals on
celestial bodies as a new scientific direction. IOP Conference Series: Earth and Environmental Science, 684(1), 012004, 2021.

[7] J. Kostelecký. Určování tenzorů deformací globálních a regionálních geodetických sítí (metodika a software). Technická správa č. 1199/2013. Geodetická observatoř Pecný. 2013 (in Czech).

[8] Motion of tectonic plates [Accessed 2021-05-09]. Available at: https://www.arcgis.com/apps/MapJournal/index.html?appid=df5f94c0050b4075adfbba54fba3eaeb.

[9] Plate Tectonics [Online] 2021 [Accessed. 2021-05-10]. Available at: https://www.nationalgeographic.com/science/earth/the-dynamic-earth/plate-tectonics/

[10] Alert – Western Japan Earthquake. [Online] 2021 [Accessed 2021-05-09]. Available at: https://alert.air-worldwide.com/EventSummary.aspx?e=854&tp=31&c=1.