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ANALYSIS AND RESEARCH RESULTS OF GNSS DATA REPRESENTATIVENESS IN ESTIMATION OF MODERN HORIZONTAL MOTION OF THE EARTH'S SURFACE (ON THE EXAMPLE OF EUROPE'S TERRITORY)

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Aim. This article analyses the modern usage of GNSS data for solving problems in geodynamics and examines the level of data suitability for estimation of regional motion and deformations of the Earth's surface according to their accuracy and the overall time of observation during which the representative estimation results can be provided. **Method.** This research was prompted by the following factors: absence of clearly established motion parameters of lithospheric plates; different strategies in processing observations and related software; unregulated minimum duration of observations; the need to increase the density of the area coverage; the need to use numerous stations for specification of tectonic models, deformation analysis, area zoning, and identification of anomalous zones of potentially dangerous geological processes. As input data, we chose three public bases of time coordinate series of stations within the Eurasian plate in Europe that are in the SOPAC archive: SIO database, formed as a result of processed observations in GAMIT-GLOBK (177 stations), and two JPL databases (204 stations) where coordinate series are obtained by processing observations using GIPSY-OASIS and combined QOCA-solution. Subject to empirical investigation for each database were coordinate series during the period 1.01.2005–1.01.2015 with a one month sampling interval. The experiment aimed at determining such integrated motion parameters of the surface under study like the weighted arithmetic linear offsets, vector length and direction, and velocity. These parameters are computed for all stations after their culling according to two formal representativeness criteria: 1) absolute values of stations offsets are greater than their average squared errors; 2) absolute values of an offset are greater than their marginal errors. According to these criteria, we determined stations that were culled most often and, thus, needed to thoroughly and individually analyzed during their usage for the purposes of geodynamics. **Results.** The experiment results showed that the minimal duration of observations is not constant and must be determined for each set of empirical data. According to the most optimistic estimates, the millimeter accuracy of motion parameters computation can be achieved after more than 2.5 years observation and usage of coordinate time series of the JPL (QOCA) database. This period is achieved using both criteria for culling of the observation period of 2005–2008 that approximately fits the limits of the official ITRF version. The centimeter accuracy under the same conditions can be achieved after more than 0.8 of a year. For the entire 10 year research period, the specified periods are more than doubled. The only explanation for such considerable differences is that they are the consequence of the motion and unadjusted position of the origin of the ITRS. **The scientific novelty and practical significance.** The obtained results indicate that there is a need to introduce a modern ITRF and to adjust the position of the origin more frequently. If the specified minimal periods are adhered to, the culling according to the marginal criterion is inappropriate because as a result many stations are discarded. The experiment results proved the advantages of QOCA solutions in terms of usage of the obtained coordinate time series comparing to GIPSY-OASIS and GAMIT-GLOBK.

Key words: GNSS observations; accuracy of coordinate time series; recent crystal motion; linear displacements and velocities.

Introduction

The research of modern motions and offsets of the Earth's surface is a topical problem not only for modern geodesy but also for many other natural sciences and manufacture areas. The territories where intense geodynamic processes take place pose a threat to the society in terms of life safety. They require continuous comprehensive monitoring which not only proves the very existence of such processes but also determines the parameters of the modification level, the degree of infestation areas, and the risks to safety. This problem is a subject of comprehensive research integrating interdisciplinary scientific cooperation.

Geodetic methods for geodynamic processes monitoring is the main source of quantitative information regarding the space-time structure of the phenomenon. Until recently, geodetic monitoring covered mainly geodynamic polygons. Active development and production of modern satellite technology that is based on the use of global geodetic networks and satellite positioning systems opened new prospects for researching the problem.

Nowadays, a global geodetic network is a complex of modern high-tech measuring devices that are harmonically combined in Global Geodetic Observing System (GGOS). GGOS is a system of observations of the International Association of Geodesy (IAG) that provides the geodetic infrastructure, which is required for monitoring the "Earth" system and studying global changes. As a part of resolving the problem, the system provides evaluation of dangerous geological processes by remote monitoring of the force fields and physical surface of the Earth using Very Long Baseline Interferometry (VLBI), Satellite Laser Randing (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and most often, Global Navigation Satellite System (GNSS). The latter is used within the networks of permanent GNSS stations, which are monitored by International GNSS Service (IGS).

Accumulated in the GGOS, databases of observations became a perfect solution of the problem. The purpose and strategic research areas of the problem are defined in the IAG resolutions by Commission 3 "Earth Rotation and Geodynamics" [http://iag.dgfi.tum.de/fileadmin/handbook_2012/333_Commission_3.pdf/].

Analysis of the research and unsolved aspects of the general problem

Depending on the nature and type of space-time fluctuations, modern motion of the Earth's surface is arbitrarily divided into three types: 1) slow trend motion of global and regional scale with speed of several millimeters to ten centimeters per year, which are caused largely by the secular drift of lithospheric plates and raise of glacial crust; 2) fast motion of the same order and scale with periodicity of hours or days to a year that occur due to internal processes in the Earth's crust, tides, atmospheric, and hydrologic seasonal load; 3) non-recurrent quick motion – instant surface offsets of local scale with an amplitude up to tens of meters, which occur within a few minutes due to strong earthquakes.

None of these types of surface motion occurs separately. They are linked together as they have common geophysical origin. Both individual researchers, their teams, and numerous specialized research institutions pay much attention to their study. Most current research problems in this context are focused on defining motion by various numerical parameters and they fit into the framework of global tectonic models of the Earth. The theory of plate tectonics is put as the basis for creation of the models. This is the latest mobilistic tectonic concept of mutual motion of lithospheric plates as absolutely hard spherical segments of the lithosphere under the condition of sustainable radius of the Earth. Plate motion is caused by mantle convection and their interaction is manifested within narrow marginal deformation zones – faults that outline the plate and determine the georeference of the most intense tectonic, seismic, and volcanic activity of the Earth. Tectonic models are divided into two types: geological and geodetic depending on the origin of input data that is used for their creation.

Classic examples of the first type are the models NUVEL-1 [DeMets et al., 1990] and NUVEL-1A [DeMets et al., 1994]. More detailed and accurate geological models are PB2002 [Bird, 2003], MORVEL [DeMets et al., 2010] and NNR-MORVEL56 [Argus et al., 2011; http://www.geoscience.wisc.edu/~chuck/MORVEL/]. Besides defining geometric forms and georeferences of lithospheric plates, the models define the ratio of horizontal and angular velocities of motion and rotation and linear velocities, which are expressed in the Cartesian coordinate system. Based on the data from comprehensive geological and geophysical monitoring of the Earth. From a chronological point of view, such parameters have a long-term nature and are expressed by the measures of geological time scale. If for creation of the first geological models the usage of geodetic data was rather limited, then for such models as MORVEL and NNR-MORVEL56, a full range of results from the remote monitoring of the Earth by the methods of satellite geodesy that were accrued at the moment of verification was used. In particular, a set of velocities GEODVEL [Argus et al., 2010], that were defined by the methods of GNSS, VLBI, SLR and DORIS, was used as well. For this reason, the latter models are often referred to as geological-geodetic.

Numerical characteristics of motion of the Earth's surface, which are determined by the methods of satellite geodesy for almost the past 25 years, allow to present the tendencies of reciprocal motion of lithospheric plates more accurately than global geological models. In addition, they can transmit and predict current short-term plate motion as well as define their internal laws of deformation, which is caused by regional and local tectonic processes. The last factor violates the hypothesis of the absolute rigidity of major lithospheric plates; however, it reveals objective prospects for usage of geodetic methods data for allocating microplates with relative motion parameters of higher numerical order or anomalous features of their spatial distribution. Such prospects are implemented in the second type of global tectonic models of the Earth – geodetic.

Usage of high-precision satellite geodesy data to study the motion of plates is directly linked with the creation of the International Terrestrial Reference System (ITRS), the general principles of which were adopted by the IAG General Assembly in 1991. The ITRS origin is placed in the center of masses of the solid Earth, oceans, and atmosphere under the condition of conservation of angular momentum of the Earth as a whole, which is consistent with the concept of zero total angular momentum of all lithospheric plates. This condition is called No-Net-Rotation (NNR). Therefore, ITRS is a non-inertial geocentric system that rotates with the Earth and allows the expression of motion of lithospheric plates with absolute numerical parameters.

As the results of observations with methods of satellite geodesy in the ITRS readout system accrued and became consistent with the then existing geological models, empirical models of plate motion of the exclusively geodetic origin began to arise. These include, for example, the model REVEL [Sella et al., 2002], GSRM-1 [Kremer et al., 2003] and its updated version GSRM v.2.1 [Kremer et al., 2014], the already mentioned GEODVEL [Argus et al., 2010] and ITRF2008-PMM [Altamimi et al., 2012]. The latter model along with GSRM v.2.1 provides by far the most accurate absolute levels of motion of fixed plates. For example, the estimated computation accuracy of ITRF2008-PMM is 0.3 mm / year [Altamimi et al., 2012], while for model MORVEL, it equals 0.67 mm / year [DeMets et al., 2010].

Comparison of absolute and relative motion parameters of lithospheric plates within geodetic and geological models shows sometimes even unreasonably significant differences. For example, the values of the linear velocity of the Eurasian plate, which from kinematic point of view is considered to be one of the most stable, fluctuating between 19-26 mm / year according to different models. Similar estimates for some of the most tectonically active plates differ tenfold. These differences are the result of various approaches to assessment of motion parameters and meaning of tectonic models of the Earth. Analysis of the latter made it possible to identify some inconsistencies that can be interpreted as follows:

1. Models MORVEL and NNR-MORVEL56 are based on the updated geological-geophysical and geodetic databases. Therefore, the basic models NUVEL-1 and NUVEL-1A can be considered as the ones that lost their relevance at the present time. This fact is proven by the articles [DeMets et al., 2010; Argus et al., 2010, 2011; Altamimi et al., 2012].

2. Relative motion parameters of an individual plate within the same geological models can differ depending on the selection of another adjacent plate taken as fixed. The resulting estimations of the plate motion are offset and differ by a systematic error, which can be approximately expressed by the motion indicator of the fixed plate. Considering the hypothesis that fixed plates do not exist, the usage of relative motion parameters is a priori subjective. Their practical use is justified only in the scope of studying the interaction of plates, although, for resolution of geodynamic problems, the use of absolute motion parameters is more appropriate.

3. Absolute motion parameters of lithospheric plates depend on establishing the origin of the geocentric ITRS and considering its velocity. In this regard, there are two directions of geodetic research of plate motion.

3.1. Most studies estimate the velocities assuming that the center of the Earth is fixed for ITRF versions under the NNR condition. Corresponding sets of velocities can be identified as ITRFVEL (sometimes GVEL) [Altamimi et al., 2002, 2007, 2011] or, for example, ITRF2008-PMM [Altamimi et al., 2012] and REVEL [Sella et al., 2002]. The main differences between these models is that the corresponding velocities of the plates are computed taking into account the offsets of the origin of the geocentric system between its ITRF versions and based on different sets of base station observations or even different modified methods for data processing. For example, the offset of the origin between ITRF2000 and ITRF2005 is amended with 0.1, 0.8 and 5.8 mm (with an accuracy of ±0.3 mm), and its velocity with an accuracy of ±0.3 mm / year is estimated by the components 0.2, 0.1 and 1.8 mm / year in the directions of coordinate axes respectively [Altamimi et al., 2007]. The same parameters between ITRF2005 and ITRF2008 are estimated at -0.5, -0.9 and -4.7 mm with an accuracy of ± 0.2 mm and 0.3, 0.0, 0.0 mm / year with an accuracy of ± 0.2 mm / year [Altamimi et al., 2011]. In both cases, the location of the origin was registered under the condition of zero transition in relation to the average center of the mass of the Earth, defined by the SLR method.

3.2. According to the arguments [Argus et al., 2010], the previous approach is not always confirmed in practice. The translational velocity of the origin of the geocentric system, according to the authors, is not a constant as the unacceptably large differences between ITRF versions demonstrate. For example, the linear velocity of its motion in the ITRF2005 differs from ITRF2000 by 1.8 mm / year and from ITRF1997 by 3.4 mm / year. In addition, in some ITRF versions, the position is different and the velocity of the origin is determined accordingly. Thus, in ITRF1997, the origin is defined by the joint processing of observation data using methods of GNSS, VLBI, SLR as the geometric center of the solid Earth shape; its velocity is the average velocity of the Earth's surface determined under the hypothesis of the sustainability of its motion within the NUVEL-1A. In ITRF2000 (and in the following ITRF versions), the origin has already been taken as the Earth center of mass, oceans, and atmosphere under the NNR condition, and its velocity is determined by the SLR observation of an orbit LAser GEOdynamics Satellite (LAGEOS) [Altamimi et al., 2002]. In order to eliminate these inconsistencies, the velocities GEODVEL are determined under the hypothesis that the origin is the center of mass of the solid Earth [Argus et al., 2010]. The components of geodetic velocities are computed taking into consideration the motion of the solid Earth center of mass regarding the origin of ITRF2005, amended by 0.3, 0.0 and 1.2 mm / year in the directions of coordinate axes X, Y, Z respectively. Station velocities in ITRF2000 are amended by -0.1, 0.1 and -0.6 mm / year and assigned to the same mass center. Thereafter, to adapt the set of geodetic velocities of GEODVEL to the geological MORVEL model, daily time series of coordinates of GNSS stations are transformed into plate-centric reference system [Argus et al., 2010; DeMets et al., 2010]. Therefore, the obtained results are relative parameters of plate motion. The reasoning for this kind of amendment used to eliminate systematic offset of an ITRS origin in regard to the center of spherical readout base of plate rotation (as the Earth center of mass) is presented in the article [Kogan, Steblov, 2008]. However, the research results presented in the article [Wu et al., 2011], show that ITRF2008 origin coordinates with the solid Earth center of mass at the level of 0.5 mm / year and question previous reasoning. In this regard, the article [Altamimi et al., 2012] presents a detailed comparative analysis of GEODVEL velocities set as well as velocities in other geodetic and geological models with ITRF2008-PMM velocities. The authors found significant differences in motion parameters of most plates in different models. However, the laws of motion of individual lithospheric plates persist, and correspondent parameters vary mostly within the accuracy of their calculations. These facts certify the absence of a clear objective approach to solving the outlined problems.

4. Absolute plate motion parameters depend on establishing a set of basic GNSS stations, their location, and time observations. Most models, when determining motion parameters, take into account time-series of station coordinates with continuous operation for more than three years and do not consider stations with a history of abnormal behavior or located near active faults. However, solving numerous tasks of modern geodynamics, such as specifying details for tectonic models or needs of deformation analysis requires the use of a wider range of stations as an input data total number of which is constantly increasing nowadays. Such needs (yet controversial ones) are confirmed by the results provided in the researches mentioned earlier. Thus, if we analyze the results of the motion study only within the Eurasian plate, then, for instance, according to [Altamimi et al., 2012], the north-western part of the European continent close to the Scandinavian peninsula has its own, different from the rest of the territory motion laws. Quite different tendencies of surface deformation can be observed in the Mediterranean basin [DeMets et al., 2010; Altiner et al., 2006; http://www.geoscience.wisc.edu/~chuck/MORVEL/].

According to the hypothesis in [Argus et al., 2010], the Eurasian plate must be divided into two independent parts by the Ural Mountains.

Undoubtedly, with the results of GNSS observations, all the above-mentioned motion types can be expressed, but only under the condition of sufficient representativeness of surface offsets. If you take into account the offsets that reach tens of centimeters or even meters, then the reliability of the numerical expression and interpretation results of the phenomenon raise no doubts. However, it is incorrect to accept the offsets or their velocities of the computation accuracy order as reliable. In this connection and taking into account the amount of the input data, it is appropriate to study their representativeness from these positions.

If we estimate the motion of the Earth's surface with such integrated parameters as average offsets and velocities of the surface motion that are outlined by numerous GNSS stations that are located within their boundaries, it is necessary to consider that such parameters are computed as functions of the observation results of individual stations. From the theory of computation errors, we know that the accuracy of such functions as the arithmetic mean or weighted arithmetic mean increases in proportion to the number of arguments compared to errors of the latter. Therefore, when processing data from numerous stations, errors of average offsets of any unrealistic submillimeter order can arise. However, this is only accuracy of the elementary processing method, which is inconsistent with precise input data and does not increase the latter one.

Based on that reasoning, in assessing the accuracy of medium offsets and their velocities, we need to consider the errors of observation results – station coordinates. Nowadays, the accuracy of such data is grounded enough in the reports that are posted on such portals as IGS (http://beta.igs.org/) or GGOS (http://www.ggos.org/), or in the articles [Altamimi et al., 2011; Gazeaux et al., 2013] and others. The most realistic values of coordinate errors σ, defined by the processing of immediate results of computation by different software products, are of the millimeter order.

Moreover, at the stage of establishing a set of basic GNSS stations, it is necessary to introduce their analysis in order to cull the stations according to a particular criterion of the offset representativeness. Only those stations that meet the selected criteria can provide reliable results when evaluating modern motions and deformations of the Earth's surface. A similar analysis is directly related to the definition of the observation period during which it is possible to establish reliable motion parameters. GNSS observations are conducted almost continuously and without justification of minimum duration of this period, the results may be suitable only for evaluation of instant offsets of the Earth's surface of large amplitude.

In general, such questions are discussed in the context of solving the problem of "signal-to-noise ratio". The main idea of it is to study how factors of different origin (noise) affect the observation results in order to minimize them during the next data processing, establishing reliable time series of station coordinates (signal), and evaluation of their accuracy. Noise content, analysis, and functional presentation of its components are crucial for setting realistic values of the trend in time series of GNSS observations, which, depending on its expression, ultimately determines the coordinate time series, and parameters of their accuracy. According to the origin and laws of manifestation, various factors of impact are classified into white, colored (mixed), and flicker noise. Division of corresponding effects, and the establishment and consideration of ratios with the aim of expressing the signal, make up the subject of one of the most important researches in modern geodesy. Research results can be achieved with different methods. This causes some inconsistencies between the end results, in particular, different evaluation of coordinates of stations with the same name at a given time, and different accuracy parameters. Analysis of current approaches to solving the problem, including from the geodynamical point of view, and the very vision of it, is provided in the article [Williams, 2008].

One of the research elements of the problem regarding noise separation is an expression of the velocities of the GNSS stations and the minimum duration of the observation period that is sufficient to provide reliable motion parameters in terms of standard deviation estimates. The article [Williams et al., 2004] presents arguments for establishing these estimates, based on the "general noise amplitude, duration of series of observations, and the compromise (ratio) between the trend of tectonic motion and the general trend of noise." Considering that these factors cause bias estimates and reliability of motion parameters, by the methods of spectral analysis, a series of 500 daily GNSS observations was identified as a parameter of their minimum duration and criteria for the use of a single station for solution of geodynamic problems. Subsequently, this approach to processing the incoming data became the basis for the creation of the autonomous program CATS (Create and Analyze Time Series) [Williams, 2008]. A more optimistic assessment of the minimum duration of observations (about one year) is presented in a study [Silver et al., 1999; Nikolaidis, 2002]. This result is limited by the ability to express the velocity of the station of 2–20 mm / year. The article [Mao et al., 1999] presents the arguments and results of studies, according to which the duration of station observations must be greater than two years. A criterion for selection of stations, which is used for creation of global tectonic models of the Earth (listed earlier), is a period of more than three years continuous operation.

Continuous impact and omission of some factors cause an offset of coordinate time series. Undetected offsets, depending on their location in the time series, cause subjective velocities of station motion. Moreover, if the length of the time series is large, then the cumulative effect of even small offsets can significantly distort velocities. Therefore, to define reliable motion parameters, it is important to detect such offsets on time and remove them from the coordinate series. Methods for solving this problem are divided into two groups. The first group includes the so called manual solutions. They aim at solving the problem by individual GNSS experts using their own experience and certain mathematical and graphical procedures. For example, a set of graphical tools GGMatlab, which is compatible with software package GAMIT-GLOBK Software (GPS Analysis at MIT & Global Kalman filter VLBI and a GPS analysis program) [http://www-gpsg.mit.edu/~simon/gtgk/], allows interactive viewing and manipulation of coordinate time series and station velocities to remove annual and semiannual offsets and subsequent averaged evaluation of the signal [Herring, 2003]. The second group includes automated (or semi-automated) methods of time series analysis of narrow specialization in terms of detection of the offsets of different origin. These include Picard and Lavielle Solutions, GA (named after Geoscience Australia agency) Solution, MAK2CS3D Solution, MRPCV1 Solution, Kehagias and Fortin Solution, Neyman-Pearson Solutions, FODITS Solutions (adapted to be compatible and is a part of the software system Bernese GNSS Software [http://www.bernese.unibe.ch/]), and JPL Solution (QOCA package). The latter solution provides a combined data processing by GAMIT-GLOBK and GIPSY-OASIS Software (GNSS-Inferred Positioning System and Orbit Analysis Simulation Software) [http://gipsy-oasis.jpl.nasa.gov/]. The content and effect of the usage of two groups of methods is described in the article [Gazeaux et al., 2013]. The authors confirmed the high efficiency of specialized methods for analysis of time series. It is proven that manual solutions can provide a posteriori accuracy of station velocities of even submillimeter order, and, thus, they have obvious advantages over automated solutions. At the same time, there is a focus on the need for improvements and ways to introduce the practice of methods of the second group as such, which can be massively used to analyze time series of observations from a constantly growing number of GNSS stations. Thus, inadequate removal of the offset series nowadays is one of the main reasons that make it impossible to achieve submillimeter accuracy of the coordinates and velocities of individual stations and geophysical motion interpretation at the level of less than 1 mm / year, which is unacceptable.

In general, solving numerous scientific geophysical problems requires accuracy of at least 0.1 mm / year. Along with full adequate consideration of offsets of coordinate time series, achievement of such accuracy is possible only because of spatial averaging of the data from long-term observations in regional areas under condition of sufficient coverage density by the GNSS stations [Altamimi et al., 2011; Gazeaux et al., 2013]. However, indisputable is that the duration of observations and reliability of station velocities, which are located in regions with different tectonic activity and within stable parts of lithospheric plates, varies. This factor causes discrepancies between the estimates of the noise and the signal of individual time series of station observations that is proven in the article [Dmitrieva et al., 2015]: “traditional evaluation of surface motion of the Earth, which is based on individual time series of GNSS-observations, depends on the selection of stations, and causes inconsistencies in velocities within the global tectonic models". In this regard, the authors suggest methods of noise evaluation and selection of a representative signal based on the joint processing and analysis of observational data from the stations network within the studied area.

The presented minority of research results show significant differences in defining the parameters of modern motions of the Earth's surface and the minimum allowable duration of observations that can ensure eligible GNSS data for velocities computation and solution of other geodynamic problems. The reasons for these differences lie in both the methodological basis of researches (theoretical approaches, elaboration strategies and data analysis), as well as in their empirical origin: input data for a research are from different sets of GNSS stations that cover both quantity and geographical (in terms of tectonics) location. For these reasons, our research aims at determining the level of suitability of GNSS data for evaluation of integrated parameters of modern regional motions and deformations of the Earth's surface from the standpoint of their accuracy and observations duration that can ensure the representativeness of the evaluation results. To solve the problem, we use observation data from stations located within the Eurasian lithospheric plate in Europe.

Data and processing

According to the results of GNSS observations in Europe in recent decades, different international and regional operational centers for collection, analysis and processing of data generated huge sets of coordinate time-series for stations. Databases of such operational centers can be distinguished as the most powerful in terms of the number of stations being used.

GNSS Data Center of the German Federal Agency for Cartography and Geodesy (Bundesamt fur Kartographie und Geodasie), which is identified as GDC / BKG [http://igs.bkg.bund.de/], has the authority of the Regional IGS Data Center. In addition to providing geospatial reference system in Germany, GDC / BKG coordinates spatial referencing and precise positioning across the whole of Europe. The center summarizes the research results of observations and combined coordinate solutions using Bernese GNSS Software [http://www.bernese.unibe.ch/] at 242 stations of the network EPN (EUREF Permanent Network) in 17 local European analysis centers. The accuracy of the station coordinates is declared at the submillimeter level. The final product is focused on the creation and maintenance of the European geospatial database and its use for solving the applied problems of geodesy and meteorology. Given this fact and the purpose of the Bernese GNSS Software, we consider it inappropriate to use the GDC / BKG database for the solution of geodynamic problems. This conclusion is confirmed by the empirical studies, which are listed in the article [Tadyeyev, Lutsyk, 2014].

Scripps Orbit and Permanent Array Center (SOPAC) [http://sopac.ucsd.edu/] is an international center for collection and processing of data from Earth remote sensing by the methods of satellite geodesy. SOPAC, a center at the University of California (USA), is created and funded by a number of leading federal and international research organizations. The center presents a wide range of data on provision of functioning of GPS / GNSS and observation results from over a thousand stations in about forty different global and regional networks (including more than 200 in Europe). The end products are used in geodesy, geophysics, geotectonics, seismology, meteorology, and other fields of science and manufacture, including the provision of geospatial reference system. SOPAC is a key member of IGS and serves as an international think tank. SOPAC archive contains three powerful bases of daily coordinate time series of stations.

Database of the Scripps Institution of Oceanography (SIO), University of California, contains the results of processing the observations using the system GAMIT-GLOBK Software [http://www-gpsg.mit.edu/~simon/gtgk/] – program complex for evaluation and analysis of measurements, relative three-dimensional positions of ground stations and their velocities, post-seismic deformations, satellite orbits, determining atmospheric delay, and Earth orientation parameters. The software was developed by MIT, SIO, Harvard University, Australian National University, and supported by US National Science Foundation.

Database of the Jet Propulsion Laboratory (JPL) from the Institute of Technology, University of California and USA National Aeronautics and Space Administration (NASA) contains the results of observations using the system GIPSY-OASIS Software [http://gipsy-oasis.jpl.nasa.gov/]. GIPSY-OASIS is a forecasting system and software developed at JPL and designed for geophysical studies (plate tectonics, deformation of the crust, the study of the motion of glaciers and climate), evaluation of the positions of the terrestrial GNSS stations, determination of reference systems and parameters of the Earth's rotation, modeling and determination of the accurate orbits of satellites, space platforms and air navigation service.

JPL database, which contains the results of the combined coordinate GAMIT Time Series – GIPSY Time Series and velocity computation results for independent geodetic stations, is designed to determine crust deformations. The combined solutions are obtained using the public software package QOCA (Quasi-Observation Combination Analysis) [http://qoca.jpl.nasa.gov/], which is sometimes referred to as "st_filter" (spatial-temporal filter). The program was developed at JPL and is based on the methodology of [Dong et al., 1998]. QOCA is a combination of GAMIT and GIPSY, it supports their formats (as well as the Bernese GNSS Software format), and aims at minimizing the impact of error sources associated with differences in data processing strategies of these programs. Since during the development of QOCA, the package had to be used exclusively for the needs of geodynamics, its algorithm presupposes detection and removal of all side effects at the stage of noise filtration except those of geophysical origin.

In addition to these, there are free databases of other analytic and operational processing centers for data of global and regional networks. In particular, data from the archives of Nevada Geodetic Laboratory (NGL) (University of Nevada) [http://geodesy.unr.edu/], University NAVSTAR Consortium (UNAVCO) [http://www.unavco.org/] and other is used in various applied studies. Data from UNAVCO is associated with SOPAC archives as they contain observations from the same GNSS stations and for their elaboration the already mentioned software systems are used.

Based on the given analysis, for our next researches, we choose data from the SOPAC archives – daily coordinate computations for stations that are located in Europe but distant from the boundary between the Eurasian and related lithospheric plates. Based on the analysis, we create three independent blocks of data. The first contains the results of observations in SIO using GAMIT-GLOBK. It encompasses 177 stations. This block is called "GAMIT-GLOBK" as per the software used. The second block of data includes coordinates of 204 stations that were obtained from observations processed in GIPSY-OASIS at JPL. The block is called "GIPSY-OASIS", respectively. The third block contains combined QOCA coordinates for the same 204 stations at JPL and is named "QOCA". Station location scheme is shown in Fig.1.

Linear velocities, vectors and directions of motion of individual stations, lithospheric plates or isolated areas within them are the absolute parameters that are used the most in the description of modern horizontal motions of the Earth's surface within different geodetic models. The basis for their numerical definition is the position of stations in the Cartesian coordinate system. On one hand, such definition of motions was formed historically because of using classical methods for creation of geodetic networks and for reasons of convenience of the end results visualization. On the other hand, the selection of a flat rectangular system in any of its topocentric varieties is caused by the prospect of using these inputs for strain analysis of the areas under study. After all, the vast majority of modern evaluation methods of strain state is based on the theory of a local-homogeneous linear deformation of the continuum, which involves the use of this particular coordinate system.

The prospect of conducting a full strain analysis of the areas involves a wide range of input space-time observations. Nowadays, the number of permanently functioning stations is much higher than at the time specified in the selected data blocks. However, even using these stations requires a preliminary analysis, which would ensure the establishment of representativeness of data from observations in terms of the needs of geodynamics.

In the experiment, we used coordinate time-series of the stations from 1/01/2005 to 1/01/2015 with a sampling rate of one month. Station coordinates of all three data blocks, defined in ITRF2008 on the first calendar day of each month in the selected time period, were downloaded from the server of the SOPAC archive simultaneously, processed, and graphically displayed using a specially designed software program in Python. This approach to the formation of the input data blocks made it impossible for inevitable differences between the coordinate values of the identically named stations due to their clarification during the primary processing of the observation time series in operational and analytical centers to influence the research results.

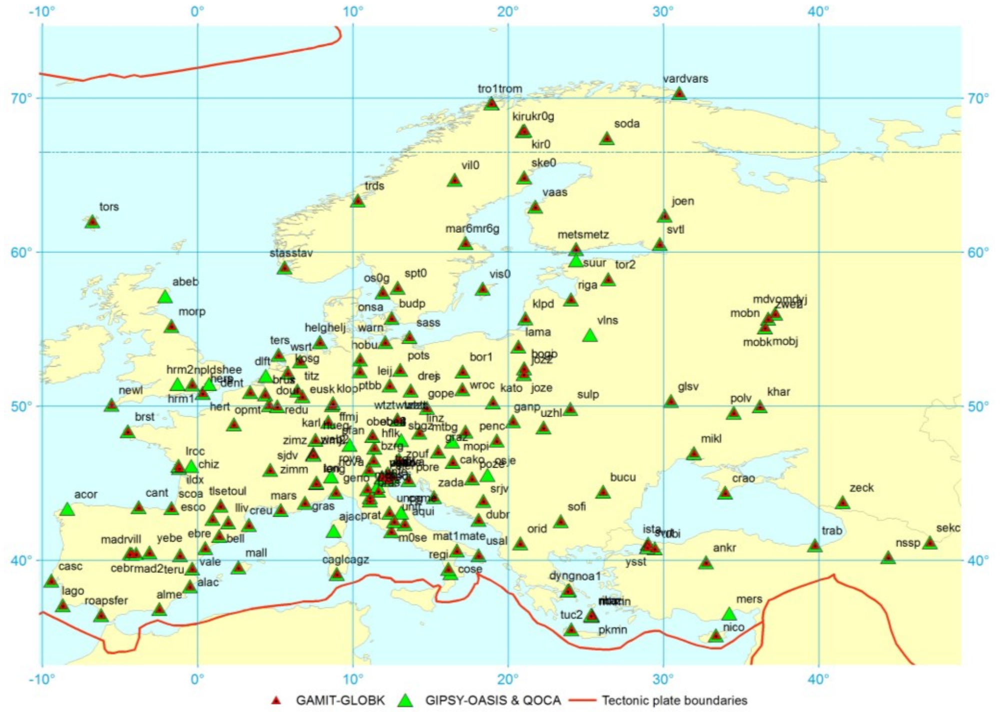

Fig. 1. GNSS-station location scheme

Given the established practice of using the rectangular coordinate system in the Gauss-Kruger projection, the next phase of the experiment involved conversion of station coordinates from the geocentric spatial into rectangular system x, y in the specified projection. The accuracy of the conversion algorithm allowed to compute the coordinates with an error of at least the millimeter order. Thus, the condition, that accuracy of computations depended only on the accuracy of the input data and not on the accuracy of the method used for their processing, was fulfilled. The results helped to define the components $\Delta x_{ik}, \Delta y_{ik}$ of the linear offset of the stations on the current date i in comparison with the final k, and estimate their accuracy by the mean squared errors $m_{\Delta x_{ik}}, m_{\Delta y_{ik}}$. The latter are determined only by the accuracy of the coordinates given in the primary database.

The following processing steps encompass performing such actions separately in the three blocks of data:

1. Definition as of the current date of weighted arithmetic mean values of the components $\Delta x_{ik}, \Delta y_{ik}$, length V_{ik} and direction (azimuth angle) α_{ik} of the offset vector and average velocity v_{ik} of the Earth's surface motion within the area outlined by all GNSS stations, as well as evaluation of the accuracy of the specified parameters by the corresponding mean squared errors.

2. Establishing criteria for representativeness

$$\left.\begin{aligned} \Delta x_{ik} &> m_{\Delta x_{ik}} \\ \Delta y_{ik} &> m_{\Delta y_{ik}} \end{aligned}\right\}, \qquad (1)$$

of the station culling that do not meet the condition (1), creation of the data sets that correspond to this condition, and their processing to determine the parameters that are set in 1.

3. Defining the same parameters using data sets that meet the threshold condition

$$\left.\begin{aligned} \Delta x_{ik} &> 3m_{\Delta x_{ik}} \\ \Delta y_{ik} &> 3m_{\Delta y_{ik}} \end{aligned}\right\}. \qquad (2)$$

Conditions (1) and (2) determine the representativeness threshold of data subject to processing. Taking them as a basis for the station culling, we will obtain a formal mathematical solution that can be valid for assessment of the integrated parameters of linear offsets and velocity of the motion of the regional scale. In evaluating the spatial structure and determining abnormal characteristics of motions and offsets of the surface, such formal approach needs improvement. Indeed, under these conditions, relatively stable, from the kinematic standpoint, stations are subject to culling.

When solving such problems, the process of culling must have a differentiated basis in order to take account of the station offsets. The effect of such approach is not considered in this paper.

Data analysis and results

Culling per the offset representativeness criteria (1) and (2) allowed to identify the stations that almost did not participate in the elaboration. The list of such stations is provided in the table. Stations culled per the criterion of representativeness $\Delta > m_{\Delta}$, of course, were culled per the criterion $\Delta > 3m_{\Delta}$ as well. See Table 1.

The results of processing of data blocks using the presented technique are illustrated by the graphs in figures 2-4. The dotted lines show the ranges of possible values of various motion parameters in terms of their standard deviation estimates.

Analysis of the data processing results during the period from 2005–2015, illustrated by graphs in Fig. 2, proves the following.

1. The average velocity computed without any culling for all three data blocks varies in the range 24–28 mm/year compared to the relatively high accuracy of these figures. This is caused by the same “exact” computation of the length of the offset vector as the weighted arithmetic mean – offset function of a great number of stations. The implications of using such parameters for the following analysis are described above. This fact is confirmed by the results of computation of the offset direction as an analytically different function of the input data: its accuracy, especially during relatively short-term periods with regard to the deadline, is very low and reaches ±50°. Thus, the previous culling of the input data per any criterion of representativeness is a necessary condition for achieving reliable outcomes.

2. More realistic results of data processing are provided by the culling per condition $\Delta > m_{\Delta}$. All stations are subject to culling with the duration of observations of at least 1.7 years in regard to the deadline. With the duration of more than 2 years, the velocities in the “QOCA” data block are stabilized at around 25 mm/year at the level of accuracy of ±1 mm/year. Errors of the average offset in this period reach the centimeter order and gradually decrease as the duration of observations increase. For “GAMIT-GLOBK” and “GIPSY-OASIS” data blocks, this tendency of the offset accuracy is observed over the duration of 2.1 years. However, this accuracy parameter (and, hence, the duration of the relevant minimum periods of observations) is clearly incompatible with the stated millimeter accuracy of determining the station coordinates. Moreover, the direction computation error observation at such length is large enough and ranges between ± (2–6°). It should be noted that the tendencies are retained for computation of the presented motion parameters and their accuracy in the data blocks using the number of stations after culling at the level ≈(10–70) %. These tendencies are observed for the duration of observations for about 5 years in the “QOCA” data block and for more than 6 years in “GAMIT-GLOBK” and “GIPSY-OASIS”. During these periods, the parameter accuracy increases. For longer periods, the offset error stabilizes at the millimeter level, and the direction acquires a clearer tendency and equals 52±1° with velocity of 25 mm/year at the submillimeter accuracy order.

3. Culling per $\Delta > 3m_{\Delta}$ causes the expression of the first, even of low accuracy, motion parameters for the observation duration of over 4 years. At the beginning of this period, only individual stations can render surface motions. The values of various parameters and their errors, which corresponds to the millimeter level of the coordinate accuracy, are stabilized when a number of stations is around 10 %. An interesting pattern can be noted: the relative stabilization of the motion parameters per such culling criterion can be observed for observation duration, which is consistent with the constant specified in the previous section, when the determination accuracy of motion parameters for the duration that exceeds the specified period correlates with the presented millimeter coordinate accuracy.

Table 1

GNSS stations culled most often during the elaboration

Culling criterion	$\Delta > m_{\Delta}$	$\Delta > 3m_{\Delta}$
Names of the culled stations	ankr dyng klpd kr0g mdvo mozi noa1 npld ober obet os0g pkmn riba srjv svrt toul trom tuc2 wett zimz zwen	aqui bogo bras brst brus brux bzrg cako cebr crao dent dubr glsv hers hflk ildx kato khar kiru linz m0se madr mad2 mdvj medi mets metz mikl mobj mobk mobn mopi mops morp newl nssp obe2 obe4 orid pore poze regi riga rove sekc sfel sfer soda sofi ters tor2 tors trab tro1 tubi untr upad usal uzhl vaas vene wtzt ysst zada zwe2

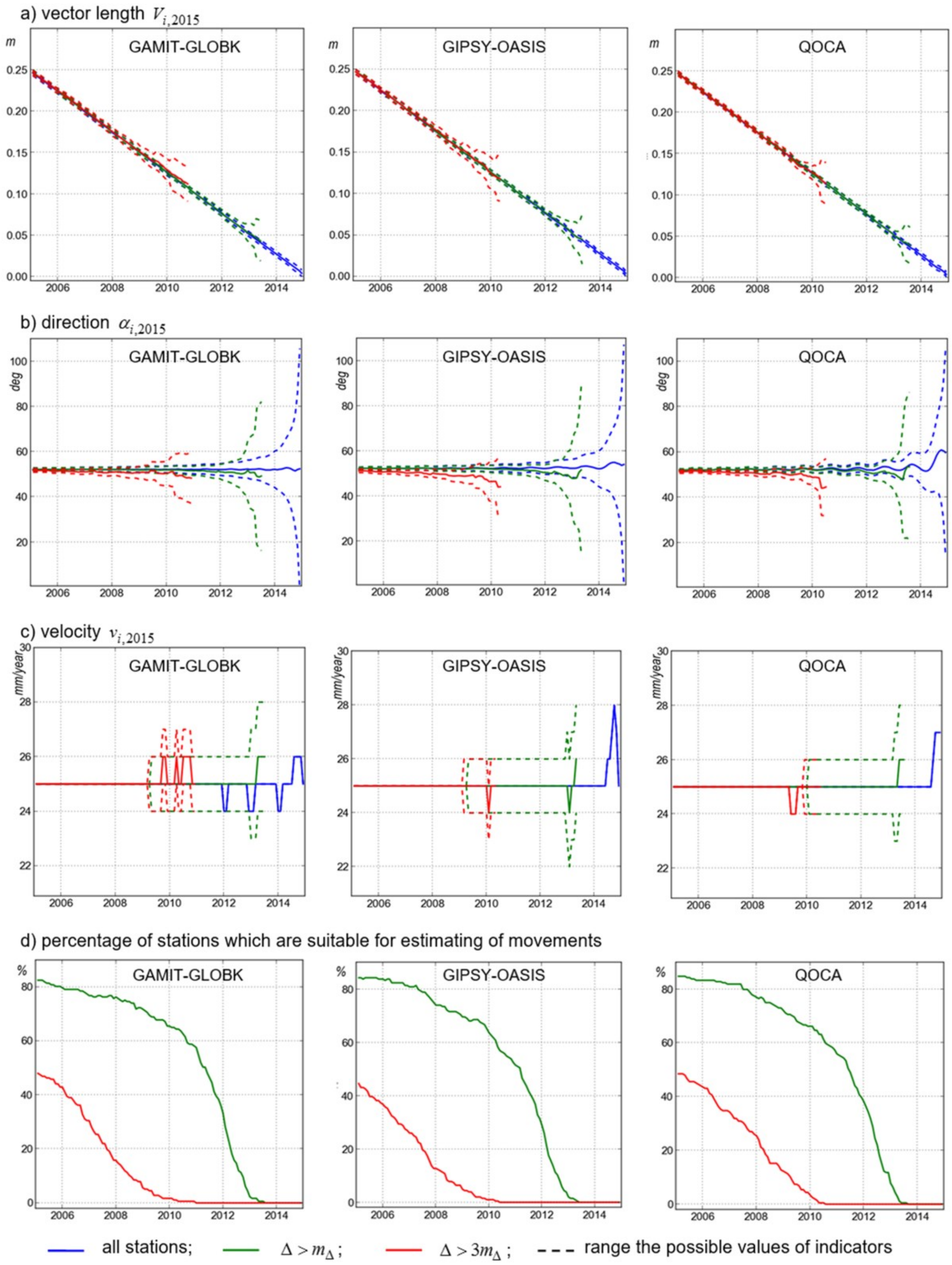

Fig. 2. Average motion parameters of the Earth's surface 2005–2015

4. Comparative analysis of the facts stated in the previous sections results in the following conclusions:

- Data processing using QOCA ensures representative (of millimeter accuracy) results of observation duration for over 5 years, and only for the duration of 2 years, we can achieve the centimeter accuracy;

- The same level of accuracy of motion parameters can be achieved using GAMIT-GLOBK and GIPSY-OASIS for data processing, but with the observation duration of more than 6 years and a bit more than 2 years;
- Data processing in GAMIT-GLOBK and GIPSY-OASIS provides almost identical final results in terms of standard deviation. A similar result is presented in the article [DeMets et al., 2010], where "the station velocity differences, computed using both software systems, did not exceed ±0.5 mm/year";
- Obtained results certify that QOCA software (and a corresponding JPL base) is more appropriate for data processing that leads to the solution of geodynamic problems, because it provides comparable, in terms of representativeness, results (compared to GAMIT-GLOBK or GIPSY-OASIS) for a shorter duration of observations;
- The number of stations after the culling per $\Delta > 3m_\Delta$ at 10 % level provides results of data processing that are identical with the ones obtained after station culling at the level of 70 % per $\Delta > m_\Delta$;
- If we adhere to the specified minimum duration of observations, then representative estimations of motion parameters can be obtained without stations culling. However, we must consider the offset accuracy according to the set weights that will minimize the impact on the final outcome with gross errors.

Analysis of the results of data processing during 2005-2008 (Fig. 3) and their comparison to the same results for period of 2005–2015 result in the following conclusions:

1. Practically all stations are subject to culling per $\Delta > m_\Delta$ in all data blocks if their observations last for less than 0.5 year. In case of culling per $\Delta > 3m_\Delta$, such minimum periods last for 2.2 years for "GAMIT-GLOBK" and about 1.7 years for 2 other data blocks.

2. When culling per $\Delta > m_\Delta$, the centimeter accuracy of parameters according to "QOCA" can be reached with observations for over 0.8 year. In "GAMIT-GLOBK" and "GIPSY-OASIS" data blocks, the same parameters were obtained with a minimum duration of 1.1 and 0.9 year respectively. Millimeter accuracy level of parameters is achieved for observations lasting for over 2.5 years, according to "QOCA", 2.8 – "GIPSY-OASIS", and more than 3 years (not even illustrated within the graphs) – "GAMIT-GLOBK". Comparison of these results with the corresponding in 2005–2015 shows a significant reduction in the duration of the minimum acceptable observation periods.

3. Other conclusions presented earlier in this article remain valid for this part of the research.

The presented results were obtained from processing observational data, if their end dates were 1/01/2015 and 1/01/2008. Similar computations are conducted also using the input data sets, where the end dates were the first calendar day of each of the intermediate years of the specified time range. This made it possible to determine the corresponding minimal duration of the periods for each end date that allows to stabilize the motion parameters both at the millimeter and centimeter accuracy level. The obtained results are presented in Fig. 4.

It shows that the minimum duration of observation is not constant and varies during the research period according to the pattern that is close to linear. From 2008 to 2015, the duration of the stabilization period has doubled. These differences, in our view, can be explained only as a result of the impact on the outcome of GNSS observations of the translational motion of the ITRS origin. This conclusion has the following arguments:

- The period of 2005–2008 approximately coincides with the dates of the official verification of relevant ITRF versions [Altamimi et al., 2007; 2011];
- The minimum duration of the observational period sufficient to achieve the stabilization of motion parameters at the millimeter accuracy during 2005–2008 and determined using different data blocks, equals 2.5–3.1 years and generally coincides with the minimum observational period as defined, for example in the studies [Argus et al., 2010; Mao et al., 1999; Williams et al., 2004]. Two preliminary arguments provide grounds to consider the specified minimum period of observation as reference period;
- In different ITRF versions, the position of the origin in the geocentric system is adjusted by the amendments that express its regular offset. The meaning and numerical order of such amendments is described in the analysis of the research problem

above. After the introduction of the ITRF2008 version, which includes coordinates of stations of all data blocks (up to 1/01/2015), such adjustments were not enforced.

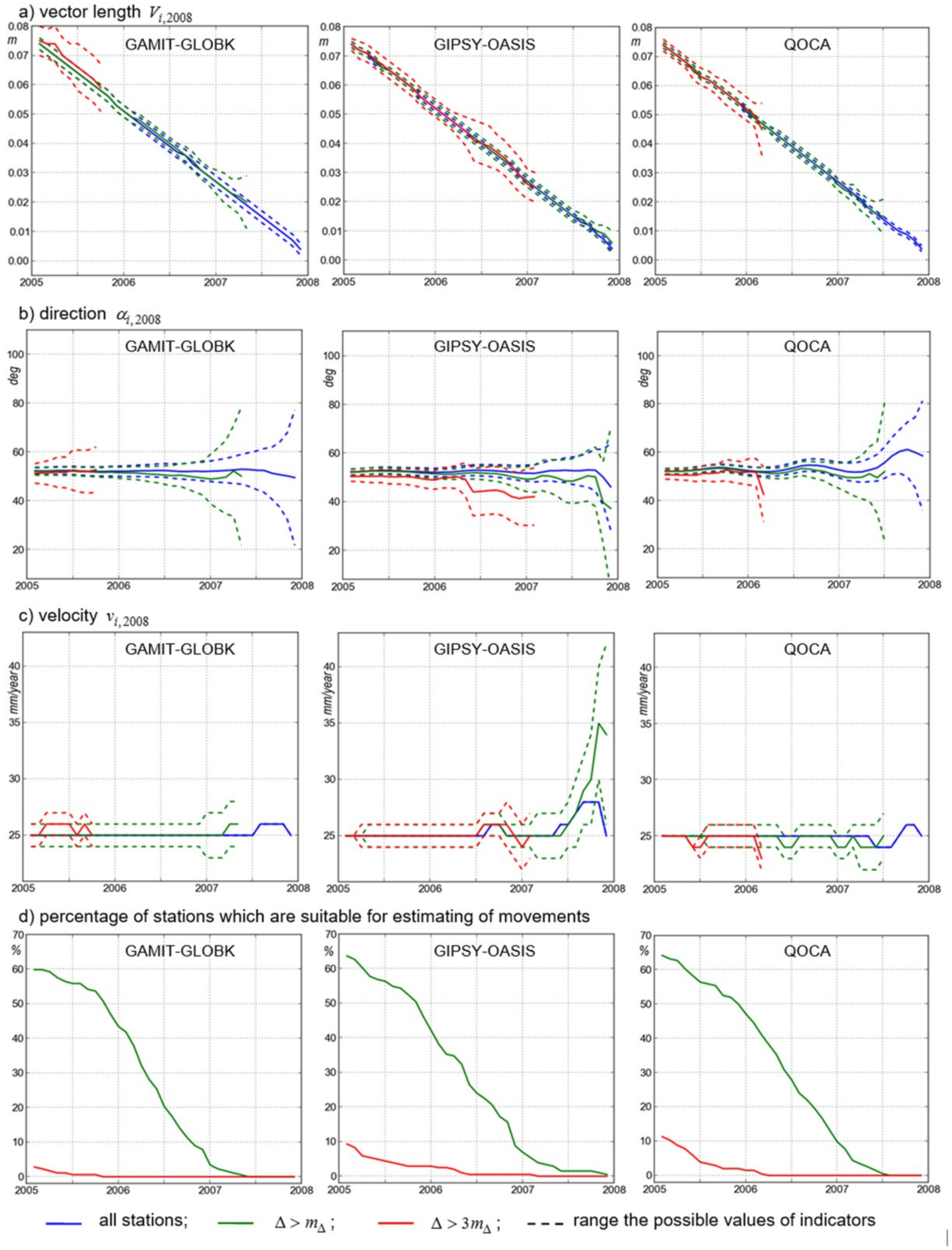

Fig. 3. Average motion parameters of the Earth's surface 2005-2008

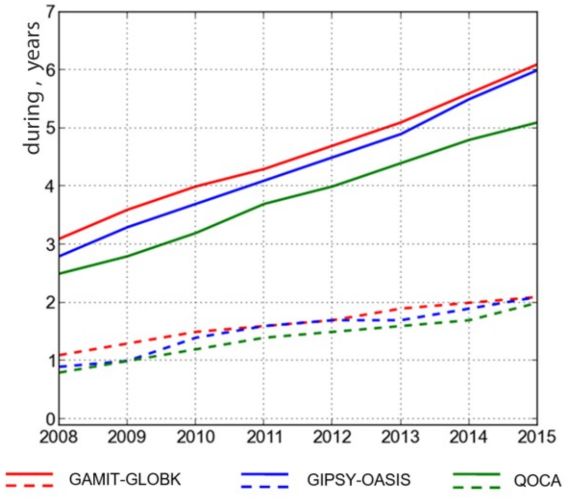

Fig. 4. Minimum duration of observational periods sufficient to achieve the parameter accuracy of the millimeter (solid lines) and centimeter level (dotted lines)

Conclusions and outlook

1. Achievement of millimeter accuracy of motion parameters that corresponds to the stated coordinates accuracy, by the most optimistic estimates, is possible for observations with duration for over 2.5 years. This result is achieved using the JPL database, which is formed by the processing of observations using QOCA. JPL databases (software package GIPSY-OASIS) and SIO (GAMIT-GLOBK) showed the same parameters for observations with duration for over 2.8 and 3 years respectively. These results ensure both equally established criteria for culling, even with the considerable screening of not representational stations considering the condition of $\Delta > 3m_{\Delta}$. However, these terms are only applicable for the period of 2005–2008 applied in the official ITRF versions. For the entire decade of the research period, the specified time frames double.

2. Centimeter accuracy of the motion parameters within the period between the same ITRF versions can be achieved after the culling per $\Delta > m_{\Delta}$ during at least 0.8 year using the JPL (QOCA) database, 0.9, and 1.1 years respectively, according to JPL (GIPSY-OASIS) and SIO (GAMIT-GLOBK). For the whole experimental period, such time frames also double.

3. Data culling per representativeness criterion $\Delta > 3m_{\Delta}$ is a perfect means of achieving reliable results, but even over the long period of observations, it leads to the screening of a large number of stations. Thus, considering the sufficient spatial coverage of areas under study by the GNSS stations, it is expedient to use culling per criterion $\Delta > m_{\Delta}$. Data processing without any culling of the stations is allowed only if observation periods, mentioned in the previous two sections, exceed. Under this condition, the accuracy of computed integrated motion parameters is almost equivalent to the one that is computed using stations culling. Otherwise, the feasibility of using GNSS data to determine integrated motion parameters is questionable, because the obtained results would provide a distorted interpretation of the phenomenon.

4. According to the conducted studies, the movement of the Earth's surface in Europe (Fig. 1) is expressed by the following absolute parameters: surface offset occurs at the velocity of 25 mm/year in the direction of 52°.

5. The obtained results prove the benefits of the combined QOCA solutions of the time series of observations, compared with the solutions obtained using GIPSY-OASIS and GAMIT-GLOBK, in terms of their use in geodynamic studies.

6. The findings presented in previous argumentations for possible impact of the translational motion of the origin of the ITRF on the results of the GNSS data processing is an attempt to motivate the identified differences between the minimally acceptable duration of observations at different times of the studied time period using the data for the geodynamic purposes. With the confirmation of this hypothesis, the obtained results, though indirectly, indicate the need to introduce the latest ITRF version of the geocentric system. This recommendation is even more relevant considering the fact that the introduction of the latest version was 7 years ago, while the longest interval between the coordinate system implementations was 5 years (2000–2005), and until 1997, the adjustments of the position of the starting point was carried out annually. Other argumentations for these differences were not found. In this regard, until the coordinate solutions are converted into the new ITRF version, the task of the previous empirical determination of the minimum duration of observations and related reliable solution of geodynamic problems has exceptional importance and relevance.

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АНАЛІЗ ТА РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ РЕПРЕЗЕНТАТИВНОСТІ GNSS-ДАНИХ В ОЦІНКАХ СУЧАСНИХ ГОРИЗОНТАЛЬНИХ РУХІВ ЗЕМНОЇ ПОВЕРХНІ (НА ПРИКЛАДІ ТЕРИТОРІЇ ЄВРОПИ)

Мета. Проаналізовано сучасний стан використання GNSS-даних для вирішення завдань геодинаміки, дослідженням ступеня придатності даних для оцінювання регіональних рухів земної поверхні з позицій критеріїв їхньої точності та тривалості спостережень, понад яку вони здатні забезпечити репрезентативні результати оцінювання. **Методика.** Мету досліджень вмотивовано відсутністю однозначно встановлених показників руху літосферних плит, відмінностями стратегій опрацювання спостережень і відповідного програмного забезпечення, неврегульованістю встановлення мінімальної тривалості спостережень, а також потребою збільшення густоти покриття територій і залучення великої кількості станцій для деталізації тектонічних моделей, деформаційного аналізу, районування територій і виявлення аномальних зон потенційно небезпечних геологічних процесів. Вхідними даними обрано три загальнодоступні бази часових координатних рядів станцій у межах Євразійської плити на території Європи, які розміщені в архіві SOPAC: база даних SIO, сформована опрацюванням спостережень у програмному комплексі GAMIT-GLOBK (177 станцій), і дві бази даних JPL (204 станції), де координатні ряди одержано опрацюванням спостережень у програмному комплексі GIPSY-OASIS і комбінованим QOCA-розв’язком. Емпіричним дослідженням осібно для кожної бази даних підлягали координатні ряди протягом 1.01.2005–1.01.2015 рр. з дискретизацією в один місяць. Суть експерименту полягала у визначенні таких інтегрованих показників руху досліджуваної поверхні як середні вагові лінійні зміщення, довжини і напрямки векторів і швидкості руху. Ці показники обчислені за усіма станціями, а також після їх вибраковування за двома формальними критеріями репрезентативності: 1) абсолютні значення зміщень станцій перевищують їхні середні квадратичні похибки; 2) абсолютні значення зміщень перевищують їхні граничні похибки. З погляду таких критеріїв виявлено станції, які вибраковувались найчастіше, тому повинні підлягати ретельному індивідуальному аналізу за їх використання для потреб геодинаміки. **Результати.** Результати експерименту показали, що мінімальна тривалість спостережень не є сталою величиною і повинна встановлюватись для кожного емпіричного набору даних. За найоптимістичнішими оцінками досягнення міліметрового рівня точності показників руху можливе при тривалості спостережень понад 2.5 років за умови використання координатних часових рядів бази даних JPL (QOCA). Такий термін досягається за обома критеріями вибраковування для періоду спостережень 2005–2008 рр., який наближено вкладається у межі офіційних ITRF-реалізацій. Досягнення сантиметрового рівня точності за таких самих умов можливе вже понад термін 0,8 року. Для усього десятилітнього дослідного періоду вказані терміни більш ніж подвоюються. Такі великі розбіжності не знайшли іншого пояснення, крім того, що є наслідком руху і не скорегованого поточного положення початку відліку референцної системи ITRS. **Наукова новизна і практична значущість.** Одержаний результат вказує на необхідність запровадження новітньої ITRF-реалізації і більш частого коригування положення початку відліку. За умови дотримування зазначених мінімальних термінів спостережень вибраковування за граничним критерієм недоцільне як таке, що зумовлює відсіювання великої кількості станцій. Результати експерименту посвідчили переваги QOCA-розв’язків, порівняно з GIPSY-OASIS та GAMIT-GLOBK, з погляду використання часових координатних рядів для потреб геодинаміки.

Ключові слова: GNSS-спостереження; бази даних; точність часових координатних рядів; сучасні рухи земної поверхні; лінійні зміщення і швидкості.

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