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THE SUSTAINABILITY OF THE ETRS89 REALIZATIONS AT NATIONAL LEVEL

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Introduction

The sustainability of reference system is determined by the choice of stations/points, fixing the coordinate system on the earth's surface, and by the completeness of considering geophysical factors, causing changes in the coordinates of the stations (for example, as a result of tectonic plates movements, tidal and load deformations of the earth's crust, post-seismic movements, etc.).

The sustainability characterizes the possibility to predict the coordinates of points at a given epoch, taking into account its average annual velocities and corrections for the influence of geophysical effects, at the same time, the geodetic network should not be subjected to deformations and maintain its maximum internal consistency. For the starting points, forming the reference system, the movement model should be well known. The deviations of the measured coordinates of points from its predictive values provide information on the unaccounted geophysical processes.

To solve scientific tasks at long time intervals, for example, in order to study sea level changes and geodynamic investigations, it is necessary not only to establish and realize the reference system of coordinates with high accuracy, but also to maintain such accuracy for a long time. This explains the high requirements for the sustainability of the coordinate system.

Analysis of the research and unsolved aspects of the general problem

The modern requirements, set by the world scientific community, regarding the quality of installation and maintenance of all-terrain reference system, are at a high level. According to [1, 2], the accuracy of its installation should not be worse than 1 mm, and its long-term sustainability should be at the level of 0.1 mm/year.

First of all, such high requirements are necessary to solve scientific tasks, since a reference system must have an appropriate metrological reserve, that is, the error of setting the coordinate system should be of much smaller value, than the amplitude of the observed phenomenon, which will enable to ensure the correct interpretation of the received data of observations.

The universally recognized standard of such system is the International Terrestrial Reference System – ITRS, which is a perfect reference system of coordinates. For the first time, it has acquired a modern content in the Resolution No. 2 of the International Union of Geodesy and Geophysics, which was adopted in 1991 in the city of Vienna, Austria. For its practical implementation within the framework of international cooperation and under the guidance of the International Earth Rotation and Reference Systems Service (IERS), four methods of space geodesy are used: radiointerferometry with very long baseline interferometry (VLBI), satellite laser ranging (SLR), Global Navigation Satellite Systems (GNSS) and the Doppler ranging and information systems – DORIS. The most accurate physical realization of the ITRS is the ITRF (International Terrestrial Reference Frame). In fact, it consists of the network of reference stations, on which measuring instruments are installed, and its main product is combined solutions in the form of coordinate directories and the vectors of constant velocity for the points of the VLBI, GNSS, SLR and DORIS-observations.

The ITRF has developed in stages and, in all, starting with the version of the ITRF88, 14 realizations of it have been published. At present, the current version is the ITRF2014 [2].

However, kinematical coordinates are not suitable for many practical applications. Thus, for instance, in geospatial relations, the "static" coordinates of special reference systems with minimized coordinate variations are widely used. In Europe, the Sub-Committee on Reference Systems (EUREF) defined the European Terrestrial Reference System of 1989 (ETRS89) as a basic. The peculiarity of the given system is its theoretically rigorous joint movement together with the Eurasian tectonic plate for the purpose of avoiding the coordinate change over time due to its natural movement. The correlation between the realizations of the ITRS reference system and the realizations of the ETRS89 are given in [6], where its official nature is stated. In fact, with the help of the indicated correlations, the coordinate transformation from the yyyy.y epoch of ITRFyy to the yyyy.y epoch of the ETRFxx can be performed.

Such transformation does not take into account the internal velocities inside the European/Eurasian plate, that is, the yyyy.y epoch remains. This means that the stations, located near fault zones, the boundaries of tectonic plates, the post-seismic effects zone, receive additional errors while transforming it from the current epoch (2018) in the ITRF2014 to the ETRS89, that is, national realizations of the ETRS89 can significantly differ from the common-European. Therefore, for some applications, the official transformation of the EUREF, according to [6], that is, without taking into account internal deformations, is not sufficient, and the creation of additional transformation fields [9] considerably complicates the accounting process. The use of 7-parameter transformation (3D-Helmert-transformation) can be considered the most optimal, and different parameters for different years can be applied to consider tectonic effects and vertical movements.

Methodology and results of work

The unsustainability of the reference system of coordinates, or rather its practical realization, may be due to two reasons: the change in the composition of the network reference stations and the continuous displacements of the reference stations themselves [13]. The composition of the reference stations may vary due to various reasons, for example, in connection with the reconstruction of the observation station, replacement of equipment, termination of observations due to lack of financing, etc. This leads to the change of the network configuration and is inevitably reflected on the parameters of the reference system of coordinates, such as the accuracy of the internal geometry of the network, orientation of its axes, the origin of the coordinate system, scale factor. The continuous changes in the reference stations positions consist of physical displacements of the station itself, as an element of the earth's crust, and the displacement of the reference point of the measuring instrument.

The factors, causing physical displacements of reference stations, can be classified by various features. Depending on the nature of the forces, causing such displacements, exogenous and endogenous factors are distinguished. The exogenous factors include: tides in the solid body of the Earth, the ocean, the atmosphere, non-tidal loads of the atmosphere and oceans and rotation effects. The endogenous factors are conditioned by the processes, related to the energy, occurring in the Earth's bowels, and can be divided into tectonic (tectonic plates movement and deformation of its boundaries, isostatic and seismic movements) and non-tectonic (technological, hydrological, hydrometeorological factors).

Moreover, the factors can be classified, according to its spectrum in space (global, regional and local) and time (age, annual daily, instantaneous).

The displacements of the reference point of the measuring instrument, connected with hardware peculiarities (for example, variations of the phase center of the GNSS-antenna), are calculated by relevant models, which were adopted by the IGS international service and by agreement with the IERS. The residual effects that cannot be simulated remain in the assessments of coordinates of the stations.

The generally recognised in the IERS linear model of coordinate change has two significant drawbacks: the movement of stations is non-linear, and the vectors of velocities contain errors, which can subsequently deform the network. Nevertheless, the given approach to considering the coordinate movements of the reference stations provides a fairly high accuracy of taking into account the coordinate changes of stations at a long time interval, which enables monitoring long-period processes.

However, at present, not all geophysical processes are studied in the detail and with the accuracy, which is necessary for creating accurate models of its influence on the coordinates of the stations. The examples of such geophysical processes are atmospheric (non-tidal) and hydrological loads, elastic reaction of the lithosphere on the variations of mass in river systems, periodic anthropogenic impact, connected with the pumping of groundwater, etc. [10].

Failure to take into account the influence of the enumerated factors causes changes in the coordinates of the stations, which cannot be simulated and, correspondingly, worsens the sustainability of the realization of the reference system of coordinates (over time the coordinates of the reference stations do not change in a straightforward manner, as predicted in the proposed IERS model). Nonlinearity of the change in the coordinates also occurs as a result of the actions of some part of instrumental errors, systematic errors of measurement methods, as well as due to errors in the models of taking into account the influence of the troposphere, the ionosphere.

In the Central European region, the phenomenon of post-glacial rebound, associated with post-seismic effects, does not cause internal deformations on the Eurasian tectonic plate, and it is not de facto taken into account by the EUREF while transforming. Predictive models reach 0.05 mm/year for horizontal and approximately up to 0.1 mm/year for vertical internal plate velocities.

For the past 10 years, the amount of the GNNS-stations has significantly increased, compared to the EPN network, due to the creation of national networks of active reference stations, that is, actually, the consolidation of the common-European network at the national level takes place [4]. The operators of such networks provide the opportunity to use the EUREF data of observations (RINEX-files) or ready results of their work (daily or weekly coordinate solutions in the form of SINEX files). The main purpose of the EPN networks consolidation is the use of a large potential of active stations of the national GNSS-networks both for geodesy and for the Earth sciences. All measures for the EPN consolidation require effective cooperation between data providers (the operators of national networks) and the scientific community.

It is known that for each ITRFyy there is a corresponding ETRFyy, but for realization after the ITRF2000, the EUREF recommends using the ETRF2000 as an official realization, for example, the ETRF2000 (R08) is the ETRF equivalent regarding the ITRF2008. For the ITRF2014 EUREF leaves two options: either to continue using the recommended traditional realization of the ETRF2000 or to use the new ETRF2014. The beginning of the ETRF2014 coincides with the beginning of the ITRF2014, which is an advantage in some applications. However, in most countries its national reference systems come namely from the ETRF2000 or its predecessors, therefore, it is still better to use the ETRF2000. The differences between the coordinates of the ETRF2014 and the ETRF2000 can reach 7 cm.

National realizations of the ETRS89 are based on different ITRF/ETRF and have been established for almost 20 years [12]. Before the implementation of the ETRF2000, there were often displacements between the ETRF, which can be up to a few cm in more peripheral parts of Europe [11]. Besides, the epoch of observation campaign is important for the regions, not belonging to a stable part of Europe (for example, Fennoscandia).

The following nuances are also important. Some countries have updated the coordinates of its points due to the replacement of equipment at observation stations or new data on the antennas calibration, while others do not have that. Moreover, a lot of national reference systems are not determined by any official EPN stations. This means that a separate national realization of the ETRS89 is not fully formed as a homogeneous European system, although it can be considered as one system in some practical applications.

Realization of the ETRF, based on the EPN-solutions, is more homogeneous and upgraded system. This means that it provides better coverage of the territory, than a combination of national realizations. For this reason, the ETRF, derived from the EPN-solutions, is better choice for evaluating transformation parameters. However, eventually, the ETRS89 for many users is usually associated as its national realization. Hence, it is important to choose the ETRF-solution(s) for evaluating transformation parameters, so that the differences from the national realizations were small enough.

National ETRS89 coordinates for the EPN stations, if any exist and have been submitted to the EUREF, are available on the EPN web portal. It is used for the project “Monitoring Official National Coordinates of the ETRF on the EPN Website”, which was developed by the EUREF working group [7]. The coordinates of the ETRS89 national realizations were downloaded from [3]. Since the GNSS-stations of Ukraine are not represented in the present project, in order to solve the issue of sampling the most appropriate national realizations of the ETRFyy and the epochs, which would represent the ETRS89 for the Central Eastern part of Europe, the ETRF realizations of the neighboring countries of Ukraine were chosen. The characteristics of such realizations are shown in Table 1.

Table 1

National realizations of ETRS89 in Central and Eastern Europe

Country	The name of the realization/epoch	Number of stations
Poland	PL- ETRF2000 /2011.0	19
Slovakia	SKTRF2009/ETRF2000 /2006.6-2008,5	9
Hungary	ETRS89/ETRF05 /2007.4-2008.7	44

The average epoch of the given available national realizations is 2008.5. Hence, the realization of the ETRF2000, the epoch of 2008.5, was chosen to represent the national ETRS89 in the Central Eastern Europe.

The consolidation of the EPN network is represented by a combined IGS14-solution [5], including the coordinates and velocities of the stations and is the ITRF2014 realization. The present solution, transformed to the ETRS89, according to the formulas and parameters in [6], is the realization of the ETRS89 (the ETRF2000, yyyy.y epoch). The epoch of yyyy.y depends on the epoch of the national GNSS-campaign, that is, a dominant realization of the ETRS89 at the national level. To transform the ITRF2014 to the ETRF2000, yyyy.y epoch, a software module was used [8]. Table 2 shows the scheme of such transformation.

Table 2

From- and to-system for the different 7-parameter transformations

From-system	Epoch	To-system	Epoch
EPN_A_IGS14	2018.5	ETRF2000	yyyy.y
EPN_A_IGS14	2020.5	ETRF2000	yyyy.y
EPN_A_IGS14	2022.5	ETRF2000	yyyy.y

For the purpose of predictive calculation of coordinates for the subsequent years, the transformation parameters $T_X, T_Y, T_Z, D, R_X, R_Y, R_Z$ were determined, using Helmert’s formulas (3D-Helmert). Since the rotation of the axes of the coordinate systems is small, a linearized version of the indicated formula was applied:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ETRS89} = \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} + (1+D) \times \mathbf{R} \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{ITRF\,2014},$$

де

$$\mathbf{R} = \begin{bmatrix} 1 & R_Z & -R_Y \\ -R_Z & 1 & R_X \\ R_Y & -R_X & 1 \end{bmatrix}.$$

Parameters have been estimated for the annual periods of 2018.5, 2020.5 and 2022.5. Numerical values of transformation parameters $T_X, T_Y, T_Z, D, R_X, R_Y, R_Z$ are given in Table 3.

Table 3

Parameters for different epochs

Parameter	2018.5	2020.5	2022.5
T_X (cm)	9.65	10.33	11.07
T_Y (cm)	6.28	6.50	6.69
T_Z (cm)	-11.57	-12.41	-13.25
R_X $\times 10^{-3}$ "	-2.98	-3.25	-3.51
R_Y $\times 10^{-3}$ "	-13.01	-13.73	-14.40
R_Z $\times 10^{-3}$ "	22.99	24.47	25.95
D (10^{-9})	2.92	3.10	3.28

Differences from official national coordinates are obtained by comparing the ETRF2000 of the epoch yyyy.y and the official national coordinates. In general, the differences between the indicated coordinates do not exceed 10 mm in the epoch of 2018.5, although there are some exceptions. It increases, when the ITRF2014 is extrapolated to the epoch of 2022.5. The average level of differences in coordinates is 10-15 mm in all components.

Conclusions and outlook

The necessity to study and distribute the transformation errors between the ITRS (currently, the ITRF2014) and the ETRS89 (currently, the ETRF2000-national level) allows to clarify the problems, related to the given transformation, at the regional and national level. In particular, at the regional level, the transformation from the ITRF2014 to the ETRF2000 is well presented by 7-parameter transformation, while at the national level a simple transformation may not be enough due to additional velocities within the European/Eurasian plate and the uncountable geophysical processes. Thus, the fluctuations of coordinates, caused by the given factors, can be estimated by amplitude at the level of 4-5 mm or above. It is not sinusoidal for most stations, as well as curves with an annual or semi-annual period.

When a set of GNSS-stations is used to evaluate transformation parameters, that is, in order to reconcile the national solution with the ITRF, herewith ignoring geophysical variations, as a result, the displaced parameters of the reference system are obtained, and, correspondingly, the displaced coordinates of all stations in the transformed solutions. At the same time, inclusion of the coordinate changes, related to certain geophysical phenomena, into the ITRF/ETRF model is not so easy. The main problem is that some seasonal fluctuations are connected with a systematic error, which depends on non-modeled instrumental errors, errors of measurement methods, errors of the applied models, but not on a geophysical signal.

If for the areas with pronounced post-seismic effects there are attempts to conduct stochastic prediction in the form of a deformation field, such approach would not be satisfactory for the region of the Central Eastern Europe, since the distribution errors dominate over possible deformation displacements. Therefore, the transformation parameters were calculated by dividing the national territory into independent time zones and the evaluation of each of it was conducted. Even in such case, the differences in coordinates are significant, but are little suitable for prediction.

References

1. Petit G. and Luzum B. (eds.) (2010) IERS Conventions (2010), IERS Technical Note № 36. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, pp. 179. URL: http://www.iers.org/TN36/.

2. Altamimi Z., Rebischung P., Métivier L., Collilieux X. (2017) Analysis and results of ITRF2014, IERS Technical Note № 38. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 76. URL: https://www.iers.org/Shareddocs/Publikationen/EN/IERS/Publications/tn/TechnNote38/tn38.pdf?__blob=publicationfile&v=4.

3. The national ETRS89 coordinates URL: http://pnac.swisstopo.admin.ch/divers/etrf_monitor/

4. EUREF Permanent Network: Densification URL: http://www.epncb.oma.be/_densification/

5. Class A EPN Station Positions and Velocities URL: ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_A_IGS14.SSC

6. Altamimi Z. 2017: EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems. URL: http://etrs89.ensg.ign.fr/pub/EUREF-TN-1.pdf

7. Brockmann E., 2009: Monitoring of official national ETRF coordinates on EPN web. URL: http://www.epncb.oma.be/_productsservices/coordinates/

8. EPN Transformation tool URL: http://www.epncb.oma.be/_productsservices/coord_trans/

9. Häkli P., Lidberg M., Jivall L., Nørbech T., Tangen O., Weber M., Pihlak P., Aleksejenko I., and Paršeliunas E., 2016: The NKG2008 GPS campaign – final transformation results and a new common Nordic reference frame. Journal of Geodetic Science. DOI 10.1515/jogs-2016-0001.

10. Freymueller J, 2009: Seasonal Position Variations and Regional Reference Frame Realization// From book Geodetic Reference Frames: IAG Symposium Munich, Germany, 9-14 October 2006, pp.191-196.

11. Benciolini B., Biagi L., Crespi M., Manzino A., Roggero M., 2008: Reference frames for GNSS positioning services: some problems and proposals, Journal of Applied Geodesy. - V. 2, Issue 1, pp. 53–62.

12. Figurski M, Szafranek K, Wrona M., 2009: Monitoring of stability of ASG-EUPOS network coordinates//Reports on Geodesy, z. 1/86, pp.31-41.
13. Griffiths J., Ray J, 2016: Impacts of GNSS position offsets on global frame stability//Geophysical Journal International, Volume 204, Issue 1, pp. 480–487

The sustainability of the ETRS89 realizations at national level

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The basic requirements for modern realizations of the reference systems of coordinates are considered. Among it, its long-term sustainability takes an important place, which is characterized by the possibility to predict the coordinates of the reference points, fixing the coordinate system, at a given epoch. The official EUREF transformation is not sufficient in some areas of the European continent, since it does not take into account the internal deformations, caused by non-simulated effects of different nature and scale. It is shown in the article, using the 7-parameter Helmert transformation as an example, that different parameters can be applied at separate time intervals to consider tectonic effects and vertical movements.