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The scientific potential of the Pulkovo velocity of GNSS-stations database: geodynamics of the East European Craton

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Abstract. A Velocities Data Base (VDB) for GNSS stations located on the territory of the Eastern European Platform (EEP) is being developed at Pulkovo Observatory. More than 70% of the stations belong to Russian GNSS networks. A comparison of the VDB velocities with a similar global database of the Nevada Geodetic Laboratory (NGL, USA) for common stations indicates the absence of systematic discrepancies between them, which made it possible to use the combined data from both databases for geodynamic studies in the EEP region. The kinematic parameters of the rotations of the main structural blocks of the EEP are determined and its deformation field is calculated.

Keywords: GNSS: site velocities; litospheric deformations, East European Platform

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1 Introduction

In 2023, 50 years have passed since the beginning of the development of the global navigation satellite system (GNSS) and 30 years since the beginning of its actual operation at the first, still operating, permanent GNSS stations (hereinafter simply stations). Now, according to very rough estimates, their number has exceeded 25 thousand stations, unevenly distributed across all continents. A database of station speeds (VDB) has been created and maintained in Pulkovo on the territory approximately coinciding with the Eastern European Platform (EEP) to solve a number of scientific problems, in particular, to study the geodynamics of the EEP.

In publicly available global velocity databases, the EEP territory within Russia is represented by a couple dozen stations, which limits the reliability of geodynamic estimates. In fact, there are more than a thousand stations located on it, owned mainly by departmental and commercial geodetic organizations of Russia. This disadvantage is compensated by the VDB that we support in open access (http://www.gaoran.ru/russian/database/station/databasev_rus.html), which makes it possible to preserve inaccessible material for scientific research and, most importantly, gradually lost due to its often limited shelf life in commercial geodetic enterprises. The description of the VDB, the data processing method and a number of studies based on it are reflected in our works by Gorshkov et al. (2015, 2021). Currently, about 900 stations are supported in the datadase.

The main feature of the geodynamics of the EEP is the isostatic postglacial uplift of Fennoscandia, and seismic regional activity in the north-west of the EEP. At the same time, vertical dynamics and seismicity are almost completely absent in the Russian Plain belonging to the EEP. Fennoscandian sedimentation is mainly composed of Precambrian crystalline formations of the Baltic Shield (BS), and the sedimentation of the Russian Plain, plastic in terms of deformations, rests on the Precambrian crystalline basement of the Russian Plate (RP) and partially on the Paleozoic folded basement of the Scythian Plate. The processes of interaction of these structures in the zone of their interface cause constant deformation of the Earth's crust by several millimeters per year, both vertically and horizontally. These processes have been studied in recent years by Lidberg, et al. (2010); Gorshkov et al. (2021); Kierulf, et al. (2021); Melnik et al. (2022).

2 Comparison of VDB and NGL global database

The Geological Laboratory of the University of Nevada (NGL, USA) maintains an extensive global publicly accessible database of speeds of more than 20 thousand stations (http://geodesy.unr.edu /). The data is processed by the same package (Gipsy, JPL) using the same precise positioning strategy as the VDB. The station speeds in NGL are calculated using the original method by Blewitt et al. (2016), the essence of which is a pairwise comparison of station positions strictly after a year, which, according to the authors, should eliminate the main problem in the analysis of GNSS positions associated with the presence of discontinuities or displacements of different nature in these series.

From both bases, stations with an observation duration of at least 2 years and with velocity errors not exceeding 0.8 mm/year for horizontal coordinates and 1.8 mm/year for vertical coordinates were selected for the EEP territory. In total, there were 1607 stations, 176 of them shared, which made it possible to conduct a comparative analysis of them. The data is taken up to and including May 2024.

From the comparison, it can be seen that the speed estimates in both databases are almost the same, so weighted average speeds were taken for common stations. This as well as the uniformity of the data processing methods used in both databases makes it possible to include the extensive material of the NGL database in the western territory of the EEP in a joint geodynamic analysis.

3 Geodynamics of the EEP

The volume and quality of the above data allow us to study the kinematic structure of the EEP region. From the point of view of geodynamics, the area of the Fennoscandia and the Russian Plate (RP) interface is most interesting as a place of interface of large geological structures. According to numerous geological and seismic data about the earth's crust in this zone, there are both weakened zones and, conversely, strength barriers, where areas of stress redistribution are formed under the influence of external factors.

3.1 Mutual rotation of Fennoscandia and Russian Plate

As mentioned in the introduction, the EEP is divided into numerous geological structures. The most significant of them is the crystalline Baltic Shield (BS), which represents most of Fennoscandia, and is mainly covered with sediments of the RP. The border of these formations runs through the Baltic Sea, the Gulf of Finland, Ladoga and Onega Lakes and the White Sea. Geologically, it is marked by the Baltic Ledge, stretching from the coast of Denmark across the Baltic Sea to the southern borders of Lake Ladoga. In addition, in the south, the Ukrainian shield is wedged into the EEP, and in the northeast, the EEP is interfaced with the Pechora platform.

The mutual motion of the blocks of the Earth's crust can be determined by calculating their instantaneous angular velocities. In accordance with Euler's theorem, the motion of any such solid-state blocks along the spherical surface of the Earth can be represented by rotation around some axis, the nearest point of intersection of which with the Earth's surface is called the Euler pole. The joint rotation of a set of n stations belonging to one block can be represented as $v = \Omega r$, where v is the velocity matrix of stations of size $3 \times n$ for each of the three velocity coordinates, Ω is a vector column of 3×1 of the desired angular velocities of the block, r is a vector column of $1 \times 3n$ coordinates of stations. To estimate the components of the angular velocity of the block $(W_x W_y W_z)$, a least squares method with a diagonal matrix of weights inverse to the dispersions of the corresponding station velocities is used.

Table 1. Angular velocity variations for BS and RP blocks

Block	N	dT	dV_i	Ω_x (mas/year)	Ω_y (mas/year)	Ω_z (mas/year)
BS	641	> 2		-0.094 ± 0.003	-0.518 ± 0.001	0.748 ± 0.007
BS	480	> 5	$3\sigma_1$	-0.091 ± 0.003	-0.517 ± 0.001	0.755 ± 0.006
RP	659	> 2	$4\sigma_1$	-0.019 ± 0.003	-0.484 ± 0.006	0.892 ± 0.007
RP	326	> 6		-0.114 ± 0.001	-0.536 ± 0.002	0.667 ± 0.003
RP	473	> 5		-0.094 ± 0.002	-0.526 ± 0.003	0.711 ± 0.004
EA	97			-0.085 ± 0.004	-0.531 ± 0.002	0.770 ± 0.005

The maximum range of Ω-solutions for both blocks is summarized in the Table 1. When analyzing numerous solutions for a combination of the above parameters, the remarkable stability of solutions for BS in contrast to solutions for RP turned out to be quite unexpected. The explanation for this fact may be that the RP is geodynamically heterogeneous due to its geological structure, and therefore, when changing the set of stations, different clusters of stations become dominant in the solution. The penultimate line of the Table 1 provides a solution that can be conditionally called the most likely solution for RP in terms of the totality of all solutions. Based on it, it can be concluded that, in general, there are no significant movements between RP and Fennoscandia. For comparison, the last line of Table 1 shows the solution for the entire Eurasian Plate (S) according to Altamimi et al. (2017), where only 97 stations located on the entire EA plate south of 55 degrees latitude were used to estimate Ω.

3.2 EEP deformation field

To determine the deformation field from the velocity field of GNSS stations, we used a well-known method by Shen, et al. (1996), in which the change in the velocity field at each point is modeled by the deformation field caused by this change and the solid-state movement of the block of the Earth's crust (displacement and rotation). The method was refined in terms of using a more complex two-factor weight function $G = LZ$, which allows to detail the deformation field and used as an alternative to the Delaunay triangulation usually used for these purposes. Here $L_i = e^{-R_i^2/D^2}$, $Z_i = n\theta_i/4\pi$, R_i is the distance from the interpolation point to the i-th station, D is the optimal smoothing parameter, θ_i is the angle between the direction to the selected surrounding stations, the total number of which is n.

This algorithm was implemented as a publicly available StrainTool software product by the team of authors Anastasiou et al. (2019) and applied by them to study the deformation field at 298 stations in Europe, which partially intersects with the EEP territory that we are studying in its western part. All the essential features of the deformation field according to their study are naturally concentrated in the seismically active southern part of Europe (Italy, Greece). For its central and northern regions, according to their estimates, the deformation rate does not exceed 10 nanostreins/year (hereinafter ns/g). Since there are no stations on the territory of Russia in the database they used, our study expands this area up to the Urals.

As expected, the main feature of the EEP deformation field is determined by the postglacial uplift of Fennoscandia, where expansion occurs in the North–Southeast direction with a maximum velocity of about 12 ns/year in the north of the Gulf of Bothnia. On the border with the Republic of Belarus, there is a gradual zeroing of expansion in the strip passing through the Baltic Sea, the Gulf of Finland, Ladoga and Onega Lakes, practically coinciding in this part with the Baltic Ledge, and further along the western border of the White Sea and the Kola Peninsula.

Other features already located on the RP have a local, but rather stable character, which was determined by the choice of stations with a duration of observations from 2 to 5 years. In this interval, the number of stations decreases by almost a quarter, but, thanks to selection, the accuracy of their speeds increases significantly.

Stable features include the zone of expansion in the sublatitudinal direction between Lake Ladoga and Lake Onega (up to 10 ns/year), which leaves the expansion zone in Fennoscandia. This zone is centered on the Svir River, which connects these lakes. Curiously, a smaller expansion zone is present around the Neva River, connecting Ladoga and the Gulf of Finland. The zone of weaker expansion (up to 8 ns/year) then continues south of the Rybinsk reservoir, almost coinciding with the Moscow Avlakogen in strike, but orthogonal to it in the expansion vector. Another expansion zone (5-6 ns/year) coincides in extent with the Ukrainian shield and is similar to Fennoscandia in terms of the expansion vector. Two weak compression zones (5 ns/year) in the submeridional direction in the area of the Valdai upland and on the border of the Pskov region and Belarus, they practically disappear when choosing stations with an increasing duration of observations.

4 Summary

The joint use of homogeneous processing speeds of more than one and a half thousand GNSS stations from the VDB and NGL bases on the territory of the Eastern European Platform allowed us to determine a number of its geodynamic structural features.

In general, the Baltic Shield and the Russian Plate do not have mutual rotation as separate tectonic blocks of the EEP (Table 1). At the same time, the RP is not geodynamically homogeneous in full accordance with its complex geological structure. There is a significant difference in the rotation of the western and eastern parts of the RP, approximately passing through the meridian of 29 degree East. In addition, in the calculated velocity field of the deformation field, its structure is noticeable at the level from -5 to +10 ns/year for RP. It is also expected that a zone of expansion of Fennoscandia up to 12 ns/year is allocated in the deformation field, caused by its postglacial uplift.

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