UDC 528.481

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https://doi.org/10.23939/jgd2022.02.017

DETERMINATION OF THE RECENT ROTATION POLES OF THE MAIN TECTONIC PLATES ON THE BASE OF GNSS DATA

The main goal is to determine and analyze the recent rotation poles of the main tectonic plates based on measurements of continuous GNSS stations for the period of 2002–2021. Using procedures based on the method of the least squares, we suggested an algorithm to determine recent rotation poles of tectonic plates on the basis of processing time series of daily solutions of continuous GNSS stations. The algorythm was implemented in the MathCAD software package. It uses, generalizes, and modernizes the approaches presented in previous studies. Structurally, this algorithm consists of five consecutive stages: transformation of data into an internal format; compliance check and time series filtering; determination of horizontal displacement rates; compliance check and filtering of specified velocities; determination of rotation poles. The algorithm involves the use of freely available time series of daily solutions of continuous GNSS stations, or any other data prepared in a similar format. The study has developed an algorithm to determine recent rotation poles of tectonic plates. It is based on processing time series of daily solutions of continuous GNSS stations. The algorithm was tested to define the recent rotation poles of the main tectonic plates. We determined the components of recent horizontal displacement vectors of 3169 continuous GNSS stations located on 7 large, 7 medium and 3 micro plates for the period of 2002–2021 in the ITRF2014/IGS14 reference frame. The accuracy of determining the component vectors of horizontal displacements is in the range of 0.9–6.4 mm and is on average 10–15 % of the vector length. The research allowed us to construct a map scheme of the spatial distribution of the velocity field of recent horizontal movements of continuous GNSS stations. Recent rotation poles of the main tectonic plates were determined for the period 2002–2021 in ITRF2014/IGS14 reference frame. It was established that, in general, the obtained values of recent rotation poles correlate well with known models of tectonic plate movements. This confirms the correctness of the chosen method, as well as the reliability of the obtained results. Recent rotation poles of tectonic plates are the basis for modeling and analysis of global, regional and local geodynamic processes, so their accurate determination is an urgent and necessary task. GNSS data is an alternative, and recently, practically irreplaceable basis for determining such parameters. The rapid increase in the number of continuous GNSS stations, as well as the high quality of their measurements, contributes to improving the accuracy of determining the recent rotation poles of tectonic plates, but leads to the need for their constant recalculation and refinement. The presented algorithm and the obtained results can be used to develop new and refine existing models of tectonic plate movements and reference frames, as well as to forecast the movements of the Earth’s crust.

Key words: rotation poles; main tectonic plates; time series of daily solutions; continuous GNSS stations; ITRF2014/IGS14 reference frame.

Introduction

It is known that the tectonic plate movement on the surface of the spherical Earth can be presented using Euler’s rotation theorem [Euler, 1776]: a solid body fixed at one point can be moved from one position to another by one rotation through a certain angle around a fixed axis, which passes through a fixed point [Le Pichon, 1968]. For the description of the movements of tectonic plates, the consequences that follow from this theorem are important: the movement of a solid body fixed at a certain point in time can be considered as a rotation around an instantaneous axis that passes through this point. The use of Euler’s rotation theorem [Euler, 1776] makes it possible to find a place (location of Euler’s pole) to fix the tectonic plate in space which provides the possibility of analyzing the movements inside the plates. It is necessary to take into account their following properties to model the movements of tectonic plates:

1. Plate boundaries are continuous. As a rule, spreading centers, subduction zones and transform faults correspond to large tectonic plates.
2. The hypothesis of the hardness of tectonic plates shows the use of Euler’s rotation theorem [Euler, 1776] to build quite simple models of the relative movement of plates in the geosphere.

3. Tectonic plates are considered as solid spherical shells of a certain area on the surface of the sphere and the velocity of spreading is the key information to explain their movement.

In this regard, the relative movement between any two tectonic plates can be represented as a simple rotation around the Euler pole, so Euler's rotation theorem [Euler, 1776] plays an important role in building models of the movement of tectonic plates.

The use of Euler's rotation theorem in geodynamics gave the concept of tectonic plates a quantitative character and opened the way for theoretical geology to gradually transform it from a descriptive science into an exact scientific discipline [Lobkovsky, 1988]. Khain and Poletaev in 2007 note that the rotational regime should serve as the starting point and basis for numerical and physical modeling of any geological (as well as all other) process, that is, any research in tectonophysics should begin with the analysis of the role of rotation poles in geodynamic movements.

There are enough methods to determine rotation poles, which are based on the study of fault azimuths, earthquake slip vectors and spreading velocities of mid-oceanic ridges [Chase, 1972; Minster and Jordan, 1978; DeMets et al., 1990; Argus and Gordon, 1991]. However, recently they have become an alternative method for estimating rotation poles, due to the rapid increase in the number of continuous GNSS stations, as well as the high quality of their measurements [Argus and Heflin, 1995; Sella, Dixon and Mao, 2002; Altamimi, Sillard and Boucher, 2002; Kreemer et al., 2006; Altamimi et al., 2007; Altamimi, Métivier and Collilieux, 2012; Goudarzi, Cocard and Santerre, 2015]. Currently, a long-term series of observations of continuous GNSS stations located on all continents and a large number of islands are accumulated. Obviously, based on these data, it is possible to reliably follow changes in the recent rotation poles of tectonic plates over time.

Purpose

The main purpose of the work is to determine and analyze the recent rotation poles of the main tectonic plates based on the processing of time series of daily solutions of continuous GNSS stations over the past 20 years (2002–2021).

Methodology

Using procedures based on the method of least squares, we proposed an algorithm to determine recent rotation poles of tectonic plates based on processing time series of daily solutions of continuous GNSS stations. It was implemented in the MathCAD software package (Fig. 1). It should be noted that this algorithm uses, generalizes, and modernizes the above approaches by [Marchenko et al., 2012; Tretyak, Al-Alusi and Babiy, 2018; and Savchyn, 2022].

In the proposed algorithm the input data are geographic coordinates and time series of daily solutions of continuous GNSS stations, as well as requirements for time series and determined velocities of continuous GNSS. The algorithm involves the use of time series of daily solutions of continuous GNSS stations freely available at the Nevada Geodetic Laboratory, 2022 [Blewitt, Hammond and Kreemer, 2018] or any other data prepared in a similar format.

The output data include processed (filtered) time series and determined velocities of continuous GNSS stations, as well as determined rotation poles of the studied tectonic plates.

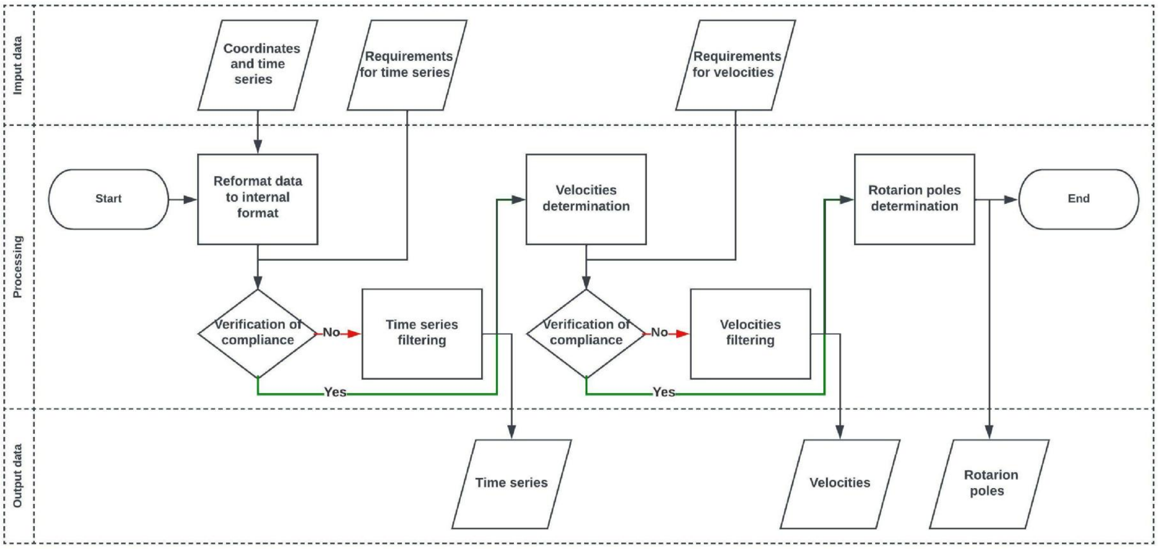

Fig. 1. The algorithm to determine recent rotation poles of tectonic plates based on processing time series of daily solutions of continuous GNSS stations

The proposed algorithm involves 5 main stages:

1. Data transformation into an internal format. At this stage, data, freely available and downloaded from the Nevada Geodetic Laboratory (2022), are transformed into the internal format.

2. Compliance check and time series filtering. Data selection is based on the criteria for continuous GNSS stations proposed by [Altamimi et al., 2017]. Detection and removal of outliers and gross errors in time series of daily solutions of continuous GNSS stations is carried out using the 3δ threshold (that is, if some value of the daily solutions was more than 3 times the standard deviation of all values, we can consider this value as an outlier and/or gross error.).

3. Determination of velocities of horizontal displacements. At this stage, linear equations are formed for all solutions of continuous GNSS stations:

$$f(t_i) = v(t_i - t_0) + y_0, \tag{1}$$

where t_i – the epoch of observation; v – linear velocity of the continuous GNSS station; and y_0 – the shift of the time series (the epoch y_0 – the initial epoch).

The system of equations for each component is solved separately by the method of least squares. The components of the velocity vectors of horizontal displacements of continuous GNSS stations are determined, and the accuracy of the defined parameters is also evaluated.

4. Compliance check and filtering of specified velocities. At this stage continuous GNSS stations with low accuracy of defining the velocities component of horizontal displacements are determined and rejected.

5. Determination of rotation poles. The mathematical apparatus presented in Marchenko et al., 2012 is used. It is based on the relationship between the components of the horizontal displacement rates of continuous GNSS stations and the rotation poles of the plate:

$$\begin{gathered} v_{B_i} = \omega \cdot \cos(\varphi) \cdot \sin(L_i - \lambda), \\ v_{L_i} = \omega \cdot [\sin(\varphi) - \cos(L_i - \lambda) \cdot tg(B_i) \cdot \cos(\varphi)], \end{gathered} \tag{2}$$

where ω – angular plate velocity; φ, λ – pole coordinates; B, L – coordinates of continuous GNSS station with defined components of horizontal displacements v_B and v_L. Such a system has a double number of equations, so the number of equations is always greater than the number of unknowns.

Systems of equations are solved by the method of least squares, using observation weights that take into account the continuity and evenness of the distribution of data throughout the observations [Tretyak, Al-Alusi and Babiy, 2018]. As a result, we will obtain the values of the recent rotation poles of the plates, as well as the accuracy of their determination.

Data

The initial data for conducting research were the coordinates and time series of daily solutions of continuous GNSS stations downloaded from the website of the Nevada Geodetic Laboratory [Blewitt, Hammond and Kreemer, 2018]. The calculations were conducted by using the GIPSY-OASIS-II software with the PPP method (Precise Point Positioning).

Currently due to the use of high-precision satellite orbits, satellite clock corrections and more advanced geophysical models in the post-production mode, the PPP method is increasingly replacing the DD method (Double Differences). For geodynamic problems, an important aspect is that this method allows obtaining coordinates independently. It does not require synchronous observations at several continuous GNSS stations, unlike the DD method. This peculiarity of the PPP method makes it possible to ignore coordinate distortions caused by other continuous GNSS stations.

Recent models divide the globe into 56 tectonic plates [Argus, Gordon and DeMets, 2011], including 7 large, 15 medium and 34 micro-plates. However, a significant number of medium and micro plates do not have enough continuous GNSS stations that meet the requirements to determine rotation poles. Therefore, in this work it was aligned to determine and study recent rotation poles of only those tectonic plates on which there are enough continuous GNSS stations that meet the requirements presented in [Altamimi et. al., 2017]. It should be noted that the boundaries of tectonic plates published in Bird, 2003 were used in the work.

As a result, a time series of daily solutions of 3,169 continuous GNSS stations located on 7 large, 7 medium and 3 micro plates are included in the processing. Fig. 2 shows the characteristics of networks of selected continuous GNSS stations separately for each studied tectonic plate. The distribution of selected continuous GNSS stations between tectonic plates is presented in Table 1 and Fig. 3.

Analyzing Fig. 2, we can observe the growth of the number of continuous GNSS stations in each network over time. It is directly related to the development and popularization of GNSS technologies. Time series of daily solutions of continuous GNSS stations are heterogeneous in time. The longest selected time series of daily solutions have duration of 20 years, and the shortest – 3 years. The main group of observations is characterized by duration of 5–15 years. However, since 2010 the time series of almost all GNSS stations have been homogeneous and continuous.

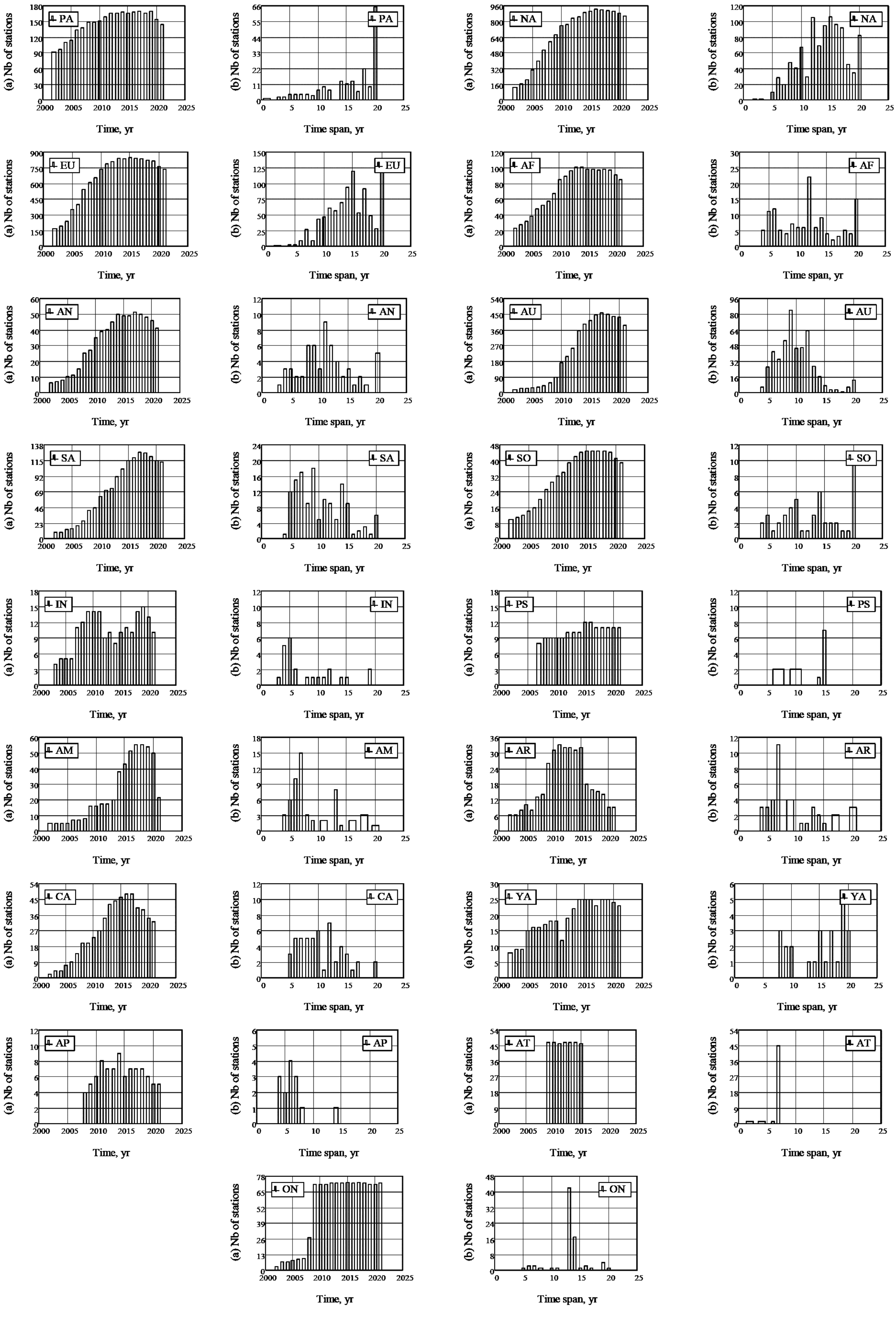

Fig. 2. Characteristics of networks of continuous GNSS stations by number of stations (a) and duration of observations (b)

Table 1

Distribution of selected continuous GNSS stations between tectonic plates

Plate Type	Plate Identifier	Plate Name	Area (sterradian)	Area (km^2)	Selected continuous GNSS stations
Major plate	PA	Pacific	2.57685	103 300 000	178
	NA	North America	1.36559	75 900 000	965
	EU	Eurasia	1.19630	67 800 000	879
	AF	Africa	1.44065	61 300 000	126
	AN	Antarctica	1.43268	60 900 000	58
	AU	Australia	1.13294	47 000 000	474
	SA	South America	1.03045	43 600 000	112
Minor plate	SO	Somalia	0.47192	16 700 000	49
	IN	India	0.30637	11 900 000	21
	PS	Philippine Sea	0.13409	5 500 000	12
	AM	Amur	0.13066	–	50
	AR	Arabia	0.12082	5 000 000	38
	CA	Caribbean	0.07304	3 300 000	46
	YA	Yangtze	0.05425	–	25
Micro plate	AP	Altiplano	0.02050	–	15
	AT	Anatolia	0.01418	–	48
	ON	Okinawa	0.00802	–	73

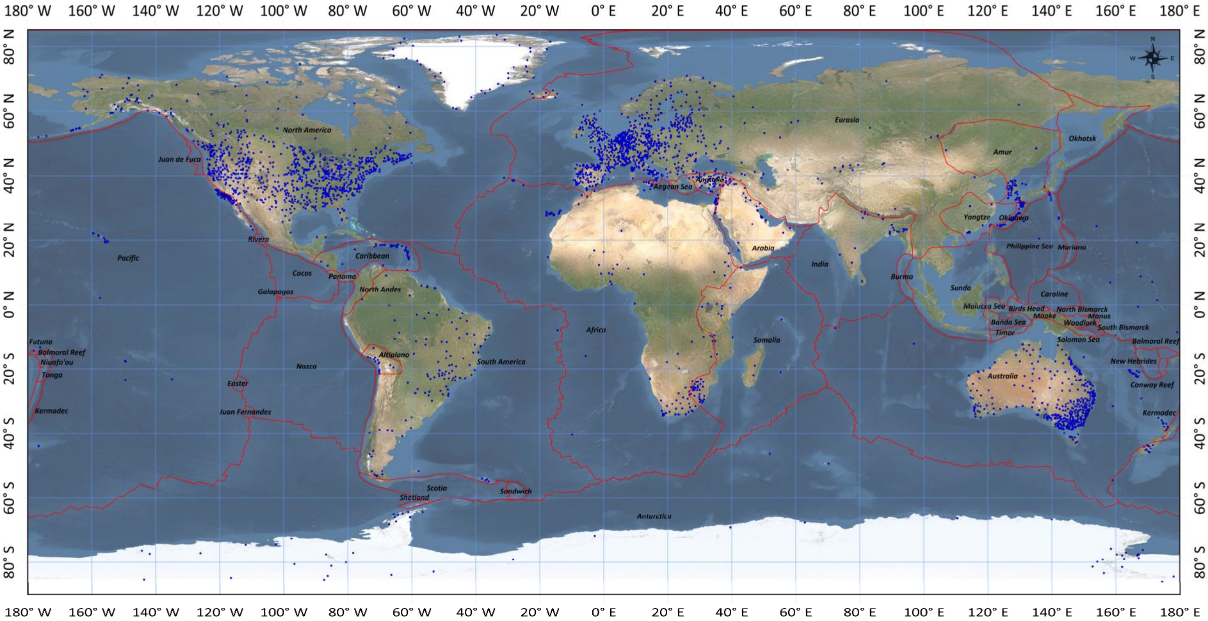

Fig. 3. Location of selected continuous GNSS stations
(The map was compiled using plate boundaries of Bird (2003))

Analyzing the results (see Table 1 and Fig. 3), it can be visible that the number of selected continuous GNSS stations for various plates is different. The least number of continuous GNSS stations was selected for PS and AP plates (12 and 15, respectively) while the largest number was selected for NA, EU and AU plates (965, 879 and 474, respectively). The density and evenness of the location of the selected continuous GNSS stations is also extremely different.

It is important to note that coordinates and time series of daily solutions of continuous GNSS stations are available on the website of the Nevada Geodetic Laboratory (2022) in the IGS14 system. Figurski and Nykiel, 2017 note that the IGS14 implementation was presented in 2017 in parallel with the redefined ITRF (ITRF2014) [Altamimi et al., 2016]. The transformation parameters between the ITRF2014 and IGS14 implementations were not published, as their global values are assumed to be zero. Due to the practical identity of these systems, the abbreviation ITRF2014/IGS14 will be used in this work.

Results

Using the proposed method, the components of the velocity vectors of horizontal displacements of continuous GNSS stations located on 7 large, 7 medium and 3 micro plates were determined for the period of 2002–2021 in the ITRF2014/IGS14 reference frame. The distribution of the determined velocities is presented in Fig. 3.

Analyzing the given map-scheme (see Fig. 3), it can be noted that the continuous GNSS stations located on the EU, AF, AU, SO, IN, AR, CA, AP and AT plates are characterized by the north-east direction of movement, but the horizontal velocity of their movements is different. So, for the EU plate the horizontal rate of movements is 17–46 mm/year, for AF plate – 19–31 mm/year, for AU plate – 35–71 mm/year, for SO plate – 20–37 mm/year, for IN plate – 30–59 mm/year, for AR plate – 30–48 mm/year, for CA plate – 5–23 mm/year, for AP plate – 13–33 mm/year, for AT plate – 4–28 mm/year.

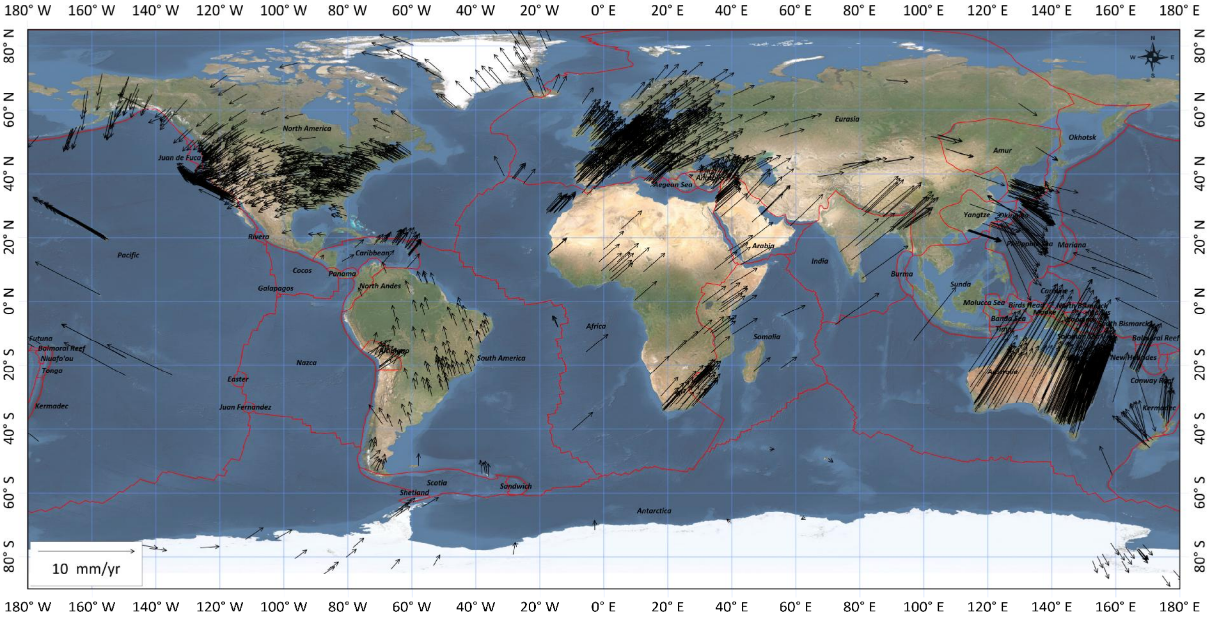

Fig. 4. Map-scheme of the distribution of horizontal displacement velocities of continuous GNSS stations (The map was compiled using plate boundaries of [Bird, 2003]

The continuous GNSS stations located on the PA and PS plates are characterized by the north-west direction, with the velocity of their movements of 32–77 mm/year for PA plate and 4–50 mm/year for PS plate.

The continuous GNSS stations located on AM, YA and ON plates are characterized by the south-east direction, with the velocity of their horizontal movement rates of 25–37 mm/year for AM plate, 29–35 mm/year for YA plate and 30–88 mm/year for ON plate.

The continuous GNSS stations located on the NA plate are characterized by the west direction of movement with a horizontal velocity of 6–31 mm/year, AN plate – the eastern direction of movement with a velocity of 4–22 mm/year, and SA plate – the north direction of movement with the velocity of 10–24 mm/year.

It should be noted that maximum displacements are identified for continuous GNSS stations located on AU, PA and YA plates, while minimum values are AN, SA, CA and AT plates.

The accuracy of determining the component vectors of horizontal displacements is in the range of 0.9–6.4 mm and is on average 10–15 % of the vector's length.

The obtained velocity values are compared with known models of tectonic plate movements NNR-NUVEL1 [Argus and Gordon, 1991], REVEL2000 [Sella, Dixon and Mao, 2002], ITRF2000 [Altamimi, Sillard and Boucher, 2002], APKIM2005 [Drewes, 2009], NNR-MORVEL56 [Argus, Gordon and DeMets, 2011] and ITRF2014 [Altamimi et al., 2017]. It was found that, in general, the obtained values correlate well with the compared models, the highest correlation was identified for ITRF2014 [Altamimi et al., 2017].

The obtained velocities of horizontal displacements of continuous GNSS stations were used to determine the rotation poles of the studied tectonic plates for the 2002–2021 period in the

ITRF2014/IGS14 reference frame. The location of the determined recent rotation poles of the main tectonic plates is given in Fig. 5.

Since the axis of rotation crosses the globe in two places, according to Cox and Hart (1986), the Table 2 presents recent rotation poles that provide a positive value of the angular velocity, determined by the right-hand rule.

The accuracy of determining the angular velocity is in the range of 0.001–0.206°/m.y. and is on average 0.5–18 % of the value of the angular velocity. The NA, EU, AF, AU and SA plates are characterized by the highest accuracy of determining the angular velocity (0.001°/m. y), whereas the CA, AT, PS, ON and AP plates (0.022–0.206°/m.y.) are determined by the lowest accuracy.

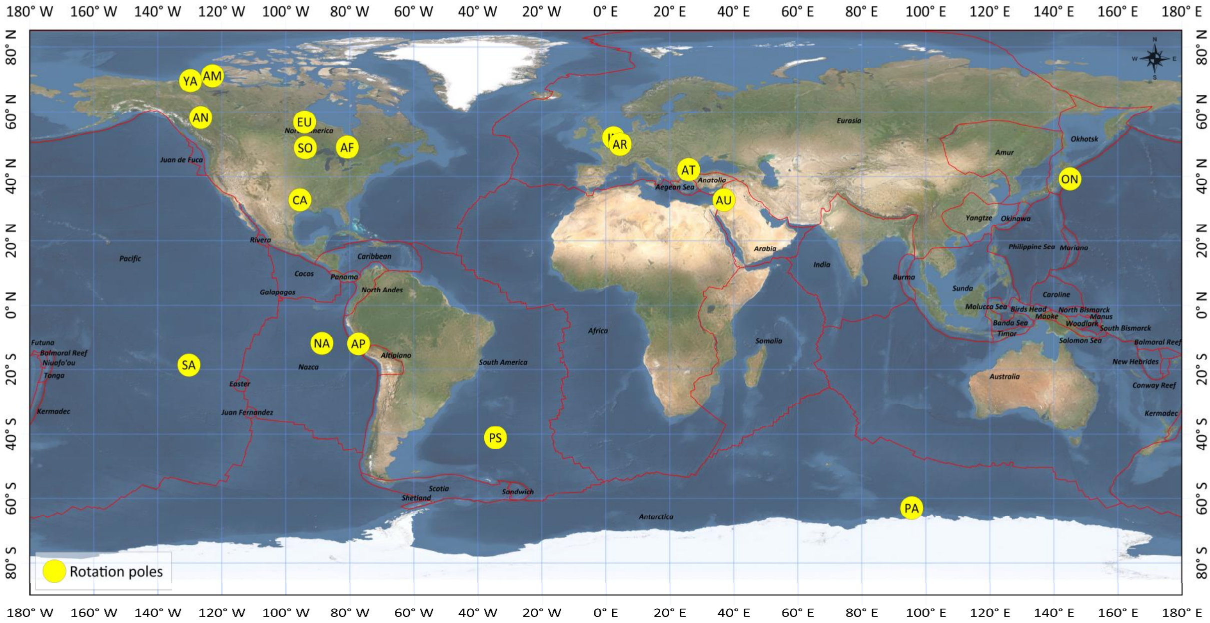

Fig. 5. The location of recent rotation poles of the main tectonic plates (The map was compiled using plate boundaries of [Bird, 2003])

Table 2

Recent rotation poles of the main tectonic plates for the period of 2002–2021 in the ITRF2014/IGS14 reference frame

Plate type	Plate Identifier	Rotation poles			Accuracy of rotation poles		
		ω, °/m.y.	φ, °N	λ, °E	m_ω, °/m.y.	m_φ, °N	m_λ, °E
Major plate	PA	0.665	–63.046	94.362	±0.006	±0.280	±0.799
	NA	0.176	–11.766	–88.722	±0.001	±0.614	±0.244
	EU	0.264	55.577	–96.888	±0.001	±0.186	±0.350
	AF	0.274	48.949	–80.786	±0.001	±0.213	±0.519
	AN	0.211	58.277	–126.531	±0.002	±0.348	±0.417
	AU	0.637	32.647	36.957	±0.001	±0.040	±0.089
	SA	0.122	–18.569	–130.232	±0.001	±0.531	±1.434
Minor plate	SO	0.303	48.824	–93.855	±0.003	±0.153	±1.119
	IN	0.525	51.980	2.623	±0.005	±0.163	±1.144
	PS	1.200	–41.033	–34.479	±0.098	±1.205	±1.153
	AM	0.327	71.209	–122.871	±0.009	±1.408	±1.444
	AR	0.578	49.907	4.477	±0.010	±0.273	±0.868
	CA	0.280	32.691	–95.533	±0.022	±1.161	±1.927
	YA	0.320	69.617	–129.762	±0.006	±1.428	±1.348
Micro plate	AP	1.152	–11.914	–77.284	±0.206	±0.906	±1.108
	AT	1.359	41.992	25.896	±0.057	±0.239	±0.382
	ON	1.308	39.783	146.054	±0.110	±0.939	±1.813

The accuracy of longitude determination is in the range of 0.089–1.927° and is on average 0.1–2 % of the longitude value. The AU plate (0.089°) is characterized by the highest longitude accuracy, while ON and CA plates (1.813–1.927°) differ by the lowest one. The accuracy of latitude determination is in the range of 0.040–1.428° and is on average 0.1–2 % of the latitude value (0.040°) is characterized by the highest latitude determination accuracy, while AM and YA plates (1.408–1.428°) are characterized by the lowest.

In general, it can be concluded that the accuracy of determining the rotation poles to a certain extent depends on the number of continuous GNSS stations used for their calculation. Therefore, the rotation poles of small and medium plates due to the small number of continuous GNSS stations are determined with worse accuracy than the rotation poles of large plates, where the number of continuous GNSS stations is excessive. Obviously, the installation of new, high-quality continuous GNSS stations on small and medium-sized plates will contribute to improving the accuracy of determining their rotation poles.

The obtained values of rotation poles are compared with known models of tectonic plate movements (Table 3) NNR-NUVEL1 [Argus and Gordon, 1991], REVEL2000 [Sella, Dixon and Mao, 2002], ITRF2000 [Altamimi, Sillard and Boucher, 2002], APKIM2005 [Drewes, 2009], NNR-MORVEL56 [Argus, Gordon and DeMets, 2011] and ITRF2014 [Altamimi et al., 2017].

Table 3

Rotation poles differences between this work and known models

Plate		Rotation pole	NNR-NUVEL1	REVEL 2000	ITRF 2000	APKIM 2005	NNR-MORVEL56	ITRF 2014	RMS
1		2	3	4	5	6	7	8	9
Major plate	PA	ϕ, °N	0.05	–1.16	–1.13	–0.15	–0.53	0.44	0.59
		λ, °E	13.04	18.38	15.83	16.14	20.34	16.98	2.26
		ω, °/m.y	0.005	–0.010	0.001	0.006	–0.014	0.014	0.010
	NA	ϕ, °N	9.27	9.38	6.73	7.47	6.92	6.58	1.16
		λ, °E	2.72	9.64	5.58	4.52	8.08	0.70	3.03
		ω, °/m.y	0.044	0.023	0.018	0.018	0.033	0.018	0.010
	EU	ϕ, °N	–4.98	2.69	2.39	–2.18	–6.73	–0.51	3.50
		λ, °E	–15.51	–5.32	–2.49	1.19	–9.61	–2.21	5.50
		ω, °/m.y	–0.024	–0.007	–0.004	–0.005	–0.041	–0.003	0.014
	AF	ϕ, °N	1.65	3.30	–	–0.85	–1.27	0.74	1.67
		λ, °E	6.79	0.61	–	1.49	12.35	–0.05	4.72
		ω, °/m.y	0.026	–0.021	–	0.005	0.018	–0.007	0.017
	AN	ϕ, °N	4.72	0.20	3.55	2.82	7.14	0.57	2.38
		λ, °E	10.63	–7.47	0.96	6.03	8.42	–0.90	6.13
		ω, °/m.y	0.039	0.015	0.020	0.032	0.039	0.008	0.012
	AU	ϕ, °N	1.15	2.21	–0.32	0.15	1.21	–0.29	0.92
		λ, °E	–3.76	1.30	2.48	–0.26	0.98	1.10	1.98
		ω, °/m.y	0.043	–0.010	–0.023	0.002	–0.005	–0.006	0.021
	SA	ϕ, °N	–6.83	–7.26	–2.89	3.97	–4.05	–0.53	3.84
		λ, °E	5.63	–5.15	–4.40	8.23	17.40	–1.66	8.00
		ω, °/m.y	–0.002	–0.016	–0.009	0.001	–0.013	–0.003	0.006
Minor plate	SO	ϕ, °N	–	4.69	–	2.48	1.13	–1.08	2.09
		λ, °E	–	–7.70	–	8.55	9.33	–4.81	7.67
		ω, °/m.y	–	0.007	–	0.005	0.036	0.029	0.013
	IN	ϕ, °N	–6.48	1.67	–	–3.78	–1.61	–0.42	2.80
		λ, °E	–2.22	–16.61	–	16.48	–5.91	–2.87	10.68
		ω, °/m.y	0.045	–0.042	–	0.063	0.019	–0.009	0.038
	PS	ϕ, °N	2.03	–5.49	–	–	–4.99	–	3.43
		λ, °E	–2.22	4.07	–	–	3.12	–	2.77
		ω, °/m.y	–0.250	–0.290	–	–	–0.290	–	0.019
	AM	ϕ, °N	–	–7.46	–	–18.41	–8.04	–	5.03
		λ, °E	–	–10.89	–	31.47	0.05	–	17.95
		ω, °/m.y	–	0.000	–	–0.059	–0.030	–	0.024
	AR	ϕ, °N	–4.71	1.56	–	–1.01	–1.03	1.27	2.25
		λ, °E	–8.88	–1.59	–	–0.68	–12.97	–11.20	5.02
		ω, °/m.y	–0.008	–0.057	–	0.021	–0.019	–0.063	0.031

Continuation of Table 3

1		2	3	4	5	6	7	8	9
	CA	*ϕ, °N*	–7.69	5.05	–	–0.09	2.51	–	4.77
		λ, °E	2.43	4.67	–	–23.37	2.91	–	11.59
		ω, °/m.y	–0.060	–0.008	–	–0.094	0.006	–	0.040
	YA	*ϕ, °N*	–	–	–	–13.02	–6.59	–	3.22
		λ, °E	–	–	–	31.56	13.14	–	9.21
		ω, °/m.y	–	–	–	–0.005	0.014	–	0.010
Minor plate	AP	*ϕ, °N*	–	–	–	–	5.33	–	–
		λ, °E	–	–	–	–	–6.70	–	–
		ω, °/m.y	–	–	–	–	–0.664	–	–
	AT	*ϕ, °N*	–	0.20	–	–1.99	–1.88	–	1.01
		λ, °E	–	0.28	–	2.10	0.76	–	0.77
		ω, °/m.y	–	–0.477	–	0.662	–0.149	–	0.479
	ON	*ϕ, °N*	–		–	–	–3.66	–	–
		λ, °E	–		–	–	–8.13	–	–
		ω, °/m.y	–		–	–	1.231	–	–
RMS		*ϕ, °N*	5.21	4.61	3.21	6.41	4.46	2.08	–
		λ, °E	8.04	8.54	6.59	13.38	9.46	6.73	–
		ω, °/m.y	0.082	0.137	0.015	0.175	0.349	0.023	–

Analyzing the obtained differences (see Table 3), we can state that there is a good agreement with known models which lends support to the validity of the chosen method, and also the reliability of the results obtained. The highest correlation is identified for ITRF2000 [Altamimi, Sillard and Boucher, 2002] and ITRF2014 [Altamimi et al., 2017] it is expected since we used the same reference frame. The lowest correlation is identified for APKIM2005 [Drewes, 2009].

The mean square deviations of the angular velocity values are in the range of 0.015–0.349°/m.y. The mean square deviations of the longitude are in the range of 6.59–13.38°, and the latitude values are in the range of 2.08–6.41°.

The least deviations of rotation poles are identified for AU and PA plates, while the largest ones are for IN and AM plates. This distribution confirms the dependence of the accuracy of determining the rotation poles of tectonic plates on the number and density of continuous GNSS stations on each plate, as well as the quality of the used time series of daily solutions of permanent GNSS stations.

Scientific novelty

Recent rotation poles of tectonic plates are the basis for modeling and analysis of global, regional and local geodynamic processes, so their accurate determination is an urgent and necessary task. GNSS data is an alternative, and recently, practically irreplaceable basis for determining such parameters. The rapid increase in the number of continuous GNSS stations, as well as the high quality of their measurements, contributes to improving the accuracy of determining the recent rotation poles of tectonic plates, but leads to the need for their constant recalculation and refinement.

Practical significance

The presented algorithm and the obtained results can be used to develop new and refine existing models of tectonic plate movements and reference frames, as well as to forecast the movements of the Earth's crust.

Conclusions

The algorithm to determine recent rotation poles of tectonic plates has been developed based on processing time series of daily solutions of continuous GNSS stations. This algorithm uses, generalizes, and modernizes the approaches presented in previous studies. It was tested to determine the recent rotation poles of the main tectonic plates.

The study determined components of the recent horizontal displacement vectors of 3,169 continuous GNSS stations located on 7 large, 7 medium and 3 micro-plates for the period of 2002–2021 in the ITRF2014/IGS14 reference frame. The accuracy of determining the component vectors of horizontal displacements is in the range 0.9–6.4 mm and is on average 10–15 % of the vector's length. The research allowed us to construct the map-scheme of the spatial distribution of the velocity field of recent horizontal movements of continuous GNSS stations.

The recent rotation poles of 7 large, 7 medium and 3 micro-plates were determined for the period 2002–2021 in the ITRF2014/IGS14 reference frame. It was established that, in general, the obtained values of recent rotation poles correlate well with known models of tectonic plate movements. This confirms the correctness of the chosen method, as well as the reliability of the obtained results.

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ВИЗНАЧЕННЯ СУЧАСНИХ РОТАЦІЙНИХ ПАРАМЕТРІВ ОСНОВНИХ ТЕКТОНІЧНИХ ПЛИТ НА ОСНОВІ ГНСС-ДАНИХ

Основні цілі роботи – визначення та аналіз сучасних ротаційних параметрів основних тектонічних плит на основі вимірювань перманентних ГНСС-станцій для 2002–2021 рр. Із використанням процедур, основаних на методі найменших квадратів, запропоновано та реалізовано у програмному пакеті MathCAD алгоритм визначення сучасних ротаційних параметрів тектонічних плит на підставі опрацювання часових рядів щоденних розв’язків перманентних ГНСС-станцій. Цей алгоритм використовує, узагальнює та модернізує підходи, наведені у попередніх дослідженнях. Структурно запропонований алгоритм складається із п’яти послідовних етапів: трансформація даних у внутрішній формат; перевірка на відповідність вимогам та фільтрація часових рядів; визначення швидкостей горизонтальних зміщень; перевірка на відповідність вимогам та фільтрація визначених швидкостей; визначення ротаційних параметрів. Алгоритм передбачає використання наявних у вільному доступі часових рядів щоденних розв’язків перманентних ГНСС-станцій або будь-яких інших даних, підготованих у аналогічному форматі. Розроблено алгоритм визначення сучасних ротаційних параметрів тектонічних плит на основі опрацювання часових рядів щоденних розв’язків перманентних ГНСС-станцій. Алгоритм апробовано для визначення сучасних ротаційних параметрів основних тектонічних плит. Визначено складові векторів сучасних горизонтальних зміщень 3169 перманентних ГНСС-станцій, розташованих на семи великих, семи середніх та трьох мікроплитах, для періоду 2002–2021 рр. у системі координат ITRF2014/IGS14. Точність визначення складових векторів горизонтальних зміщень у межах 0,9–6,4 мм та становить у середньому 10–15 % від довжини вектора. Побудовано картосхему просторового розподілу поля швидкостей сучасних горизонтальних рухів перманентних ГНСС-станцій. Визначено сучасні ротаційні параметри основних тектонічних плит для 2002–2021 рр. у системі координат ITRF2014/IGS14. Установлено, що в загальному отримані значення сучасних ротаційних параметрів добре корелюють із відомими моделями рухів тектонічних плит. Це підтверджує правильність вибраного методу, а також достовірність отриманих результатів. Сучасні ротаційні параметри тектонічних плит є основою для моделювання та аналізу глобальних, регіональних та локальних геодинамічних процесів, тому їх точне визначення є актуальним завданням, яке необхідно виконати. Альтернативною, а останнім часом і практично незамінною основою для визначення таких параметрів є ГНСС-дані. Стрімке збільшення кількості перманентних ГНСС-станцій, а також висока якість їх вимірювань сприяють підвищенню точності визначення сучасних ротаційних параметрів тектонічних плит, але призводять до необхідності їх постійного переобчислення та уточнення. Запропонований алгоритм та отримані результати можна використати для розроблення нових та уточнення наявних моделей рухів тектонічних плит і систем координат, а також для прогнозування рухів земної кори.

Ключові слова: ротаційні параметри; основні тектонічні плити; часові ряди щоденних розв’язків; перманентні ГНСС-станції; система координат ITRF2014/IGS14.

Received 03.09.2022