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Tectonic Plate Parameters Estimated in the International Terrestrial Reference Frame ITRF2008 Based on SLR Stations

Katarzyna KRASZEWSKA, Marcin JAGODA,
and Miłosława RUTKOWSKA

Technical University of Koszalin, Koszalin, Poland;
e-mails: katarzyna.kraszewska@tu.koszalin.pl,
marcin.jagoda@tu.koszalin.pl (corresponding author),
miloslawa.rutkowska@tu.koszalin.pl

Abstract

This paper concerns an analysis of the accuracy of estimated parameters Ω (Φ, Λ, ω) which define the tectonic plate motions. The study is based on the velocities of station positions published by ITRF2008 for Satellite Laser Ranging (SLR) technique. The Eurasian, African, North American and Australian plates were used in the analysis. Influence of the number and location of stations on the plate surface on estimation accuracy of the tectonic plate motion parameters was discussed. The results were compared with the APKIM 2005 IGN model. In general, a remarkable concurrence agreement between our solutions and the APKIM 2005 model was found.

Key words: tectonic plate motion, ITRF2008, SLR stations.

1. INTRODUCTION

ITRF2008 is a version of the International Terrestrial Reference Frame based on combined solutions of the four space geodetic techniques: VLBI, SLR, GPS and DORIS, spanning 29, 26, 12.5, and 16 years of observations,

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respectively (Altamimi *et al*. 2011). The ITRF2008 network comprises 934 stations located at 580 sites, with 463 in the northern hemisphere and 117 in the southern hemisphere. All SLR, GPS, DORIS, and VLBI techniques offer determination of the 3-dimensional station positions with accuracies of a few mm and the coordinate velocities of 1 mm/year from continuous observation in the time interval Δt or repeated observations after the time interval Δt. In this paper, the network of SLR stations shown in Figs. 2, 6, 10, and 11 was analyzed. Generally, this technique is based on measurement data for geodetic satellites LAGEOS 1 and LAGEOS 2 and supported by satellites such as STELLA, STARLETTE, AJISAI, and others. The method of estimation of satellite orbits, station positions and velocities is described, *e.g.*, in Lejba and Schillak (2011), Rutkowska and Jagoda (2010), and Sośnica (2014).

2. METHOD OF TECTONIC PLATE PARAMETER ESTIMATION

The plate parameters are described by angular velocities (ω_x, ω_y, ω_z) or by the rotation vector $\vec{\Omega}$ represented by geographical position of the pole rotation (Φ, Λ) and the rotational velocity (ω/Ma) (Drewes 1989) shown in Fig. 1. The station displacements are the functions of the tectonic plate parameters given in Eqs. 1 by Drewes (1989).

$$\begin{aligned} \Delta\phi &= \omega \cdot \Delta t \cdot \cos\Phi \cdot \sin(\lambda - \Lambda) , \\ \Delta\lambda &= \omega \cdot \Delta t \cdot (\sin\Phi - \cos(\lambda - \Lambda) \tan\phi \cdot \cos\Phi) , \end{aligned} \tag{1}$$

where ϕ, λ define the station position; $\Delta\phi$, $\Delta\lambda$ – the station shift, which can be estimated from Eq. 1 or station velocities; Φ, Λ, ω are the parameters of the plate motion; and ω_x, ω_y, ω_z are the angular velocities.

The angular velocities can be transformed to the parameters of the plate motion by Eqs. 2 given by Van Gelder and Aardoom (1982).

$$\begin{aligned} \mathrm{tg}\,\Phi &= \frac{\omega_z}{\sqrt{\omega_x^2 + \omega_y^2}} \\ \mathrm{tg}\,\Lambda &= \frac{\omega_y}{\omega_x} \\ \omega &= \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2} \\ \omega_x &= \omega \cos\Lambda \cos\Phi \\ \omega_y &= \omega \sin\Lambda \cos\Phi \\ \omega_z &= \omega \sin\Phi \end{aligned} \tag{2}$$

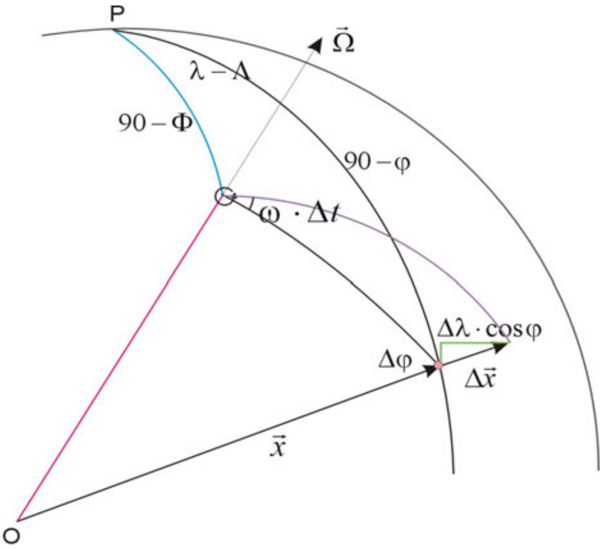

Fig. 1. Relationships between the displacement of the station position and tectonic plate parameters (Drewes 1989).

The observation equations for the least squares adjustment of plate motion parameters from coordinate shifts of stations are given by formula 3 in Drewes (1982):

$$
\begin{aligned}
v_\phi &= \left(\frac{\partial \Delta\phi}{\partial \Phi}\right) d\Phi + \left(\frac{\partial \Delta\phi}{\partial \Lambda}\right) d\Lambda + \left(\frac{\partial \Delta\phi}{\partial \omega}\right) d\omega - \left(\Delta\phi^{\mathrm{obs}} - \Delta\phi^{\mathrm{cal}}\right), \\
v_\lambda &= \left(\frac{\partial \Delta\lambda}{\partial \Phi}\right) d\Phi + \left(\frac{\partial \Delta\lambda}{\partial \Lambda}\right) d\Lambda + \left(\frac{\partial \Delta\lambda}{\partial \omega}\right) d\omega - \left(\Delta\lambda^{\mathrm{obs}} - \Delta\lambda^{\mathrm{cal}}\right),
\end{aligned}
\tag{3}
$$

and the observation equation for distance changes from coordinate shifts is:

$$
\begin{aligned}
v_{\Delta S} = {} & \left(\frac{\partial \Delta s}{\partial \Phi_i}\right) d\Phi_i + \left(\frac{\partial \Delta s}{\partial \Lambda_i}\right) d\Lambda_i + \left(\frac{\partial \Delta s}{\partial \omega_i}\right) d\omega_i + \left(\frac{\partial \Delta s}{\partial \Phi_k}\right) d\Phi_k + \\
& + \left(\frac{\partial \Delta s}{\partial \Lambda_k}\right) d\Lambda_k + \left(\frac{\partial \Delta s}{\partial \omega_k}\right) d\omega_k - \left(\Delta s_{\mathrm{obs}} - \Delta s_{\mathrm{cal}}\right),
\end{aligned}
$$

where i and k define the plate numbers on which the end-points of the baseline are situated. A system of equations can be solved if sufficient number of observations is available. For estimating the plate motion parameters using Eqs. 3, at least two points on each plate are needed. If the number of stations is greater, the unknowns can be solved using the least square method according to the following expression 4.

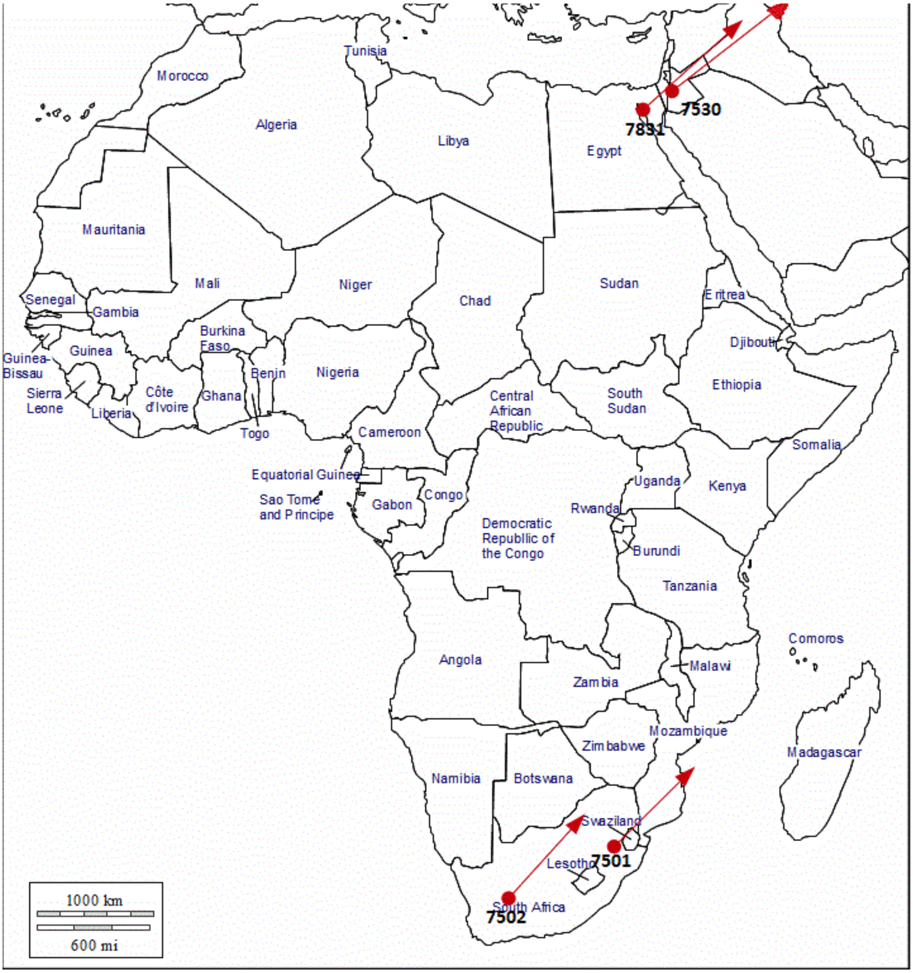

Fig. 2. Four station positions and velocity vectors used for the estimation of parameters for the African tectonic plate.

$$\Omega = \begin{bmatrix} \Phi \\ \Lambda \\ \omega \end{bmatrix} = \left(A^T P A\right)^{-1} A^T P L \,, \tag{4}$$

where A is the matrix of partial derivatives given by expressions 5, P is the matrix of measurement weights, and L is the matrix $(O - C)$, with O – the observed value, and C – the calculated value.

The sequential method was adopted for analysis. In the first step, the tectonic plate parameters were adjusted for two or three stations localized on

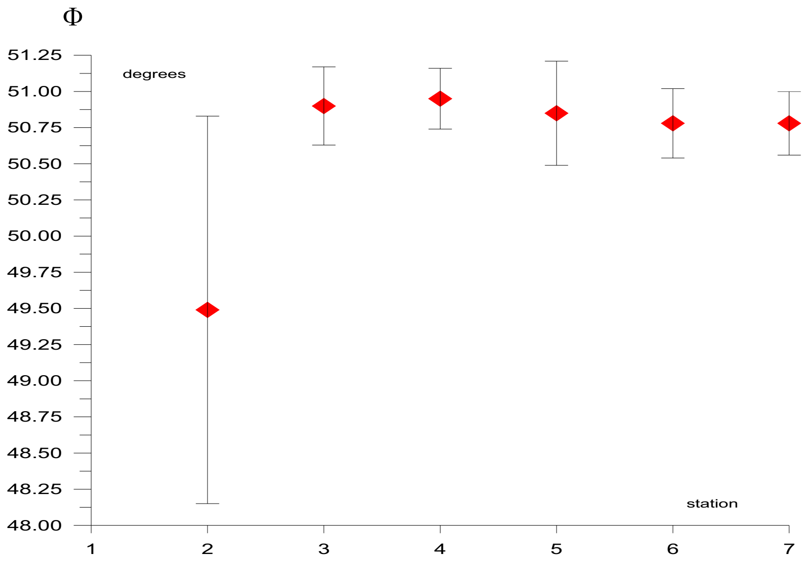

Fig. 3. Estimated parameter Φ and its error of the African plate motion for SLR network of 7 selected stations using the least square sequential solution.

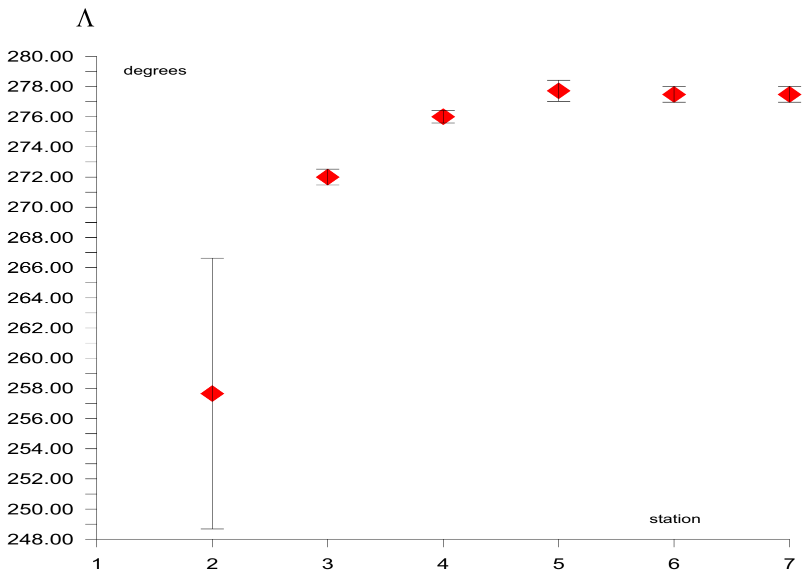

Fig. 4. Estimated parameter Λ and its error of the African plate motion for SLR network of 7 selected stations using the least squares sequential solution.

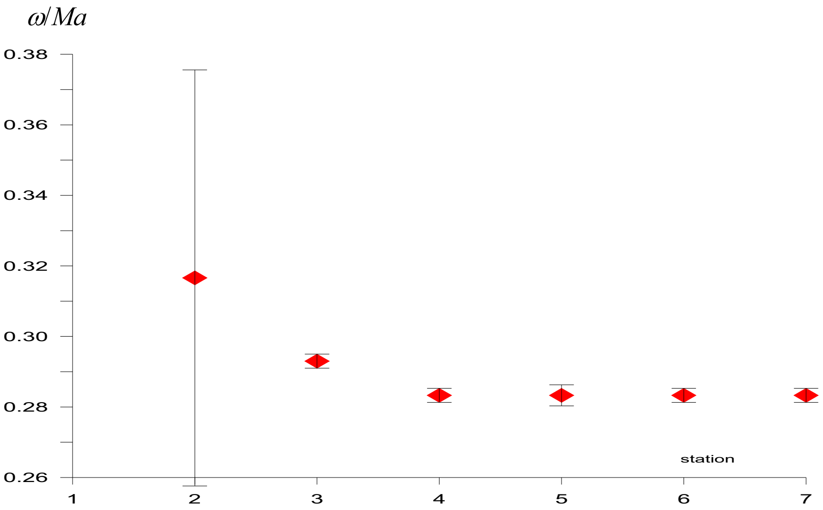

Fig. 5. Estimated parameter (ω/Ma) and its error of the African plate motion for SLR network of 7 selected stations using the least squares sequential solution.

each plate. In subsequent steps, stations one after the other were included and added to the solution. In each step, the parameters were adjusted once again, enabling the stability parameters and their errors to be observed. This is shown in Figs. 3, 4, 5 (for the African plate), 7, 8, 9 (for the North American plate), and 12, 13, 14 (for the Eurasian plate). The estimated final unknowns (Φ, Λ, ω) and their errors were analyzed. The results of the analysis are shown in Tables 1, 2, 3 for the African, North American, and Eurasian plates, respectively. Expressions for partial derivatives used in Eqs. 3 are given in the following formula 5.

$$\begin{aligned}
\frac{\partial \Delta\phi}{\partial \Phi} &= -\omega \sin\Phi \sin(\lambda - \Lambda) , \\
\frac{\partial \Delta\phi}{\partial \Lambda} &= -\omega \cos\Phi \cos(\lambda - \Lambda) , \\
\frac{\partial \Delta\phi}{\partial \omega} &= \cos\Phi \sin(\lambda - \Lambda) , \\
\frac{\partial \Delta\lambda}{\partial \Phi} &= \omega \cos\Phi + \omega \cos(\lambda - \Lambda) tg\phi \sin\Phi , \\
\frac{\partial \Delta\lambda}{\partial \Lambda} &= -\omega \cos\Phi \sin(\lambda - \Lambda) tg\phi , \\
\frac{\partial \Delta\lambda}{\partial \omega} &= \sin\Phi - \cos(\lambda - \Lambda) tg\phi \cos\Phi .
\end{aligned} \tag{5}$$

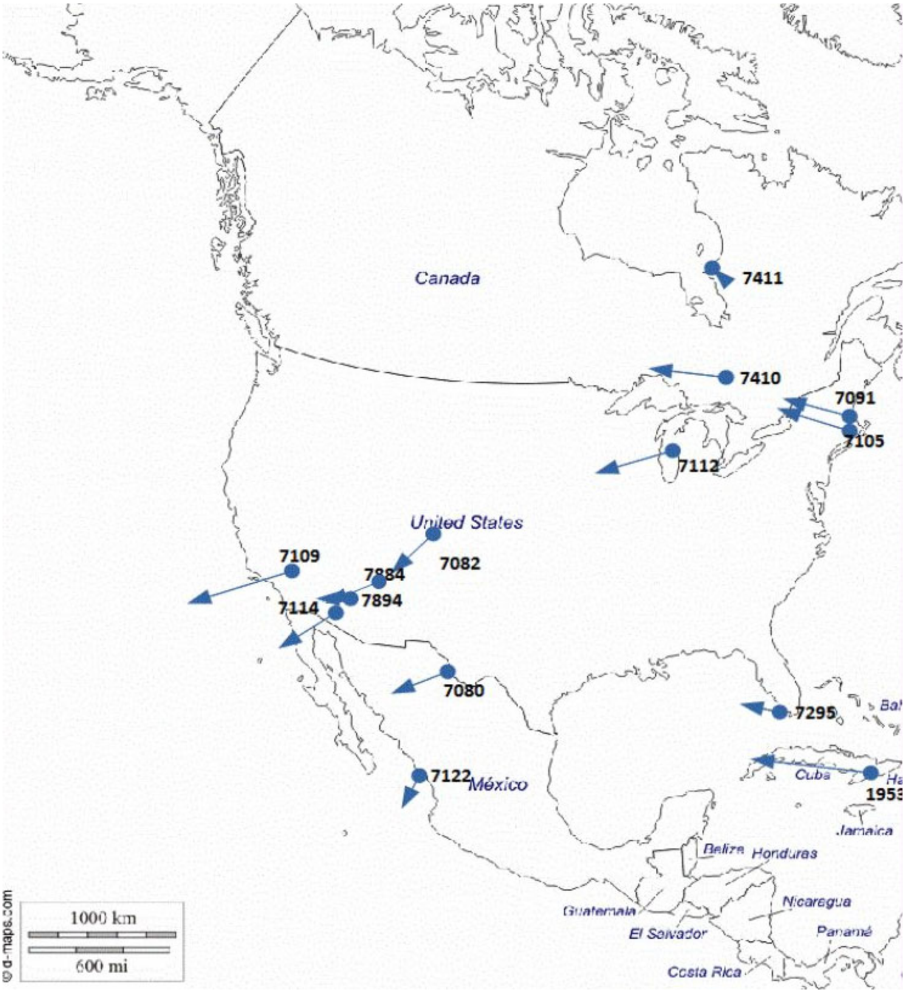

Fig. 6. The thirteen station positions and velocity vectors used for estimation of parameters for the North American plate. One station, no. 7109, was deleted from the solution, because of systematic error of adjustment. Explanation is described in the conclusions.

3. RESULTS

The paper presents the tectonic plate motion parameters Ω (Φ, Λ, ω) for the African, North American, Eurasian, and Australian plates which were adjusted using observation Eqs. 3. The idea of this paper is to show an influence of location and number of stations in each analyzed plate on estimation accuracy of plate motion parameters for SLR technique and in future for the other techniques. Our computations were performed on the basis of an im-

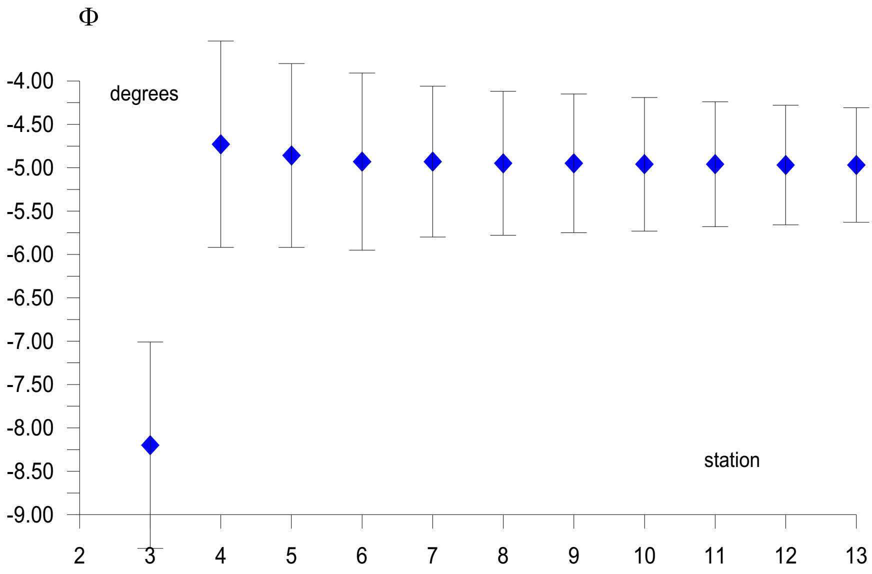

Fig. 7. Estimated parameter Φ and its error of the North American plate motion for SLR network of 13 selected stations using the least squares sequential solution.

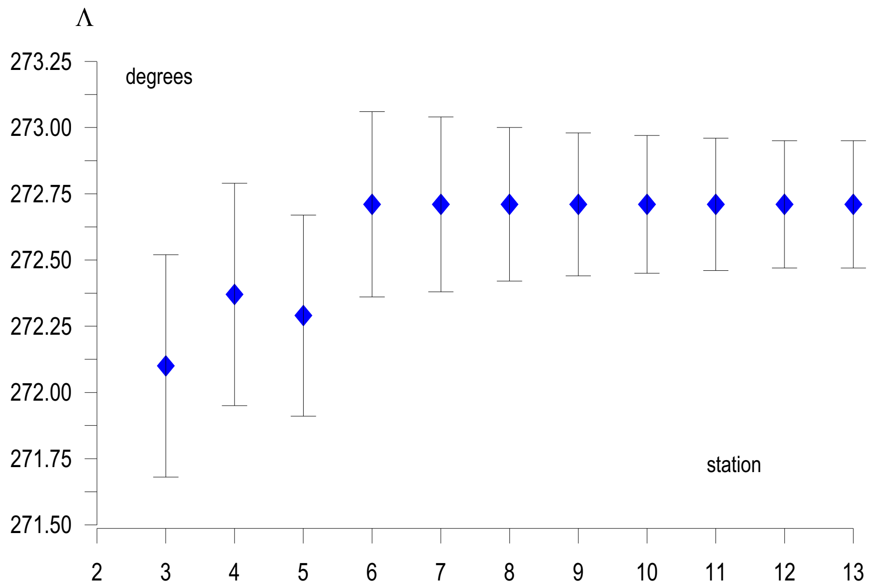

Fig. 8. Estimated parameter Λ and its error of the North American plate motion for SLR network of 13 selected stations using the least squares sequential solution.

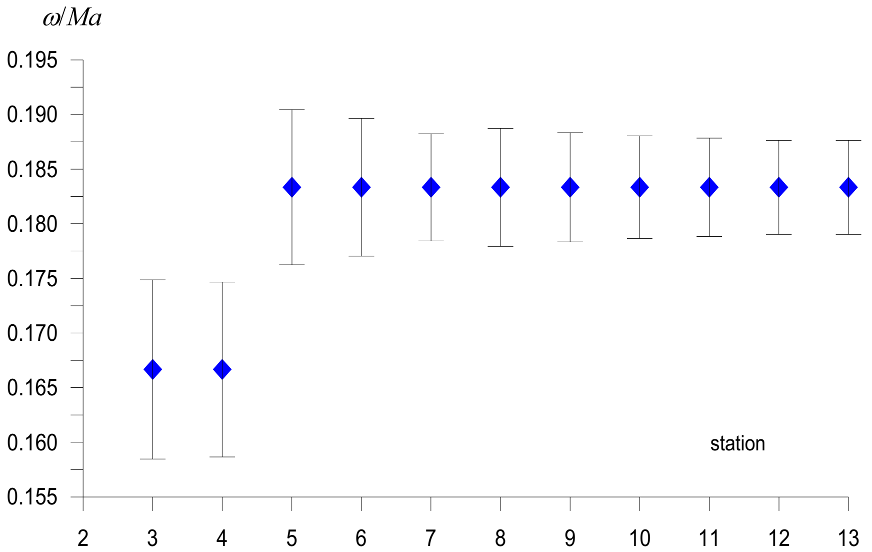

Fig. 9. Estimated parameter (ω/Ma) and its error of the North American plate motion for SLR network of 13 selected stations using the least squares sequential solution.

proved solution of the International Terrestrial Reference Frame ITRF2008 adjusted and described in detail by Altamimi *et al*. (2011). The coordinate velocities caused by the tectonic plate motions for SLR, GPS, DORIS, and VLBI techniques were taken from the paper quoted above. Generally, it must be mentioned that the number of SLR working stations is not large (about 40 on the Earth's surface) and they are not uniformly distributed. Significantly greater number of stations can be observed in the northern hemisphere than in the southern one. The minimum number of stations which is needed for estimation of the plate motion parameters is equal to 2. Greater number of stations allows to adjust solution using the least squares method. Stability of solution is observed when change of estimated value in the next step is smaller than value of computed accuracy solution. The sequential method was adopted for the analysis. In the African plate, seven SLR stations are situated only (7530, 7831, 7501, 7502, 7543, 7544, and 7939). Four stations are located on the African plate (red color vectors in Fig. 2), two stations in Mediterranean Sea (red color vectors in Fig. 10), and one station, Matera no. 7939, on European continent (blue color vector in Fig. 10). The final estimated values, $\Phi = 50.80° \pm 0.22°$, $\Lambda = 277.45° \pm 0.48°$, and $\omega/Ma = 0.283 \pm 0.002$, are given in Table 1. For the North American plate, the selected 13 SLR stations were investigated. The first estimation was per-

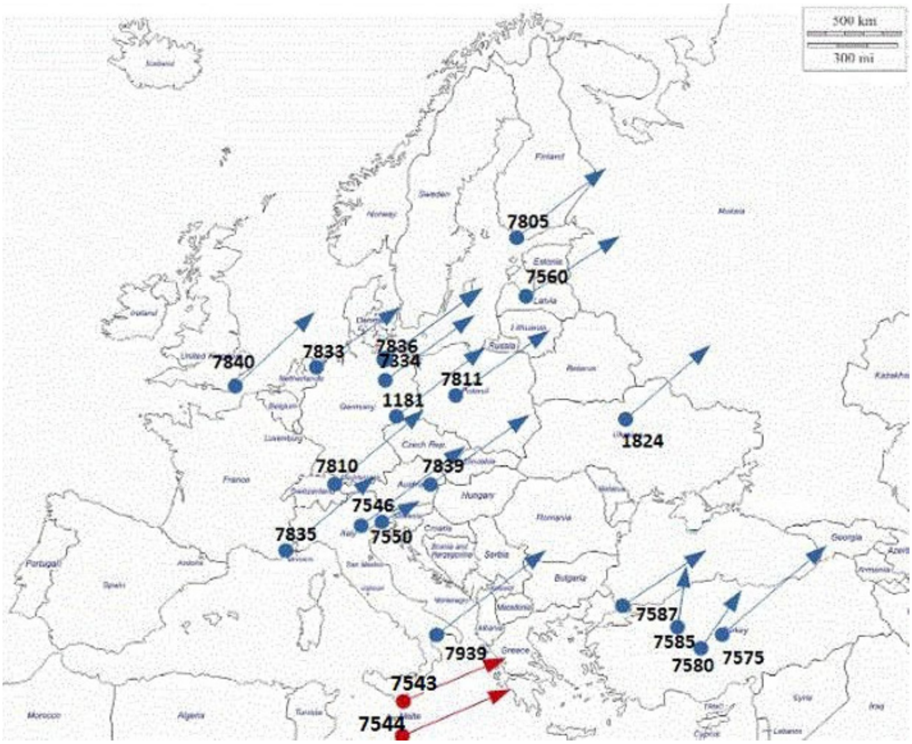

Fig. 10. Twenty two station positions and velocity vectors located on the European plate. Twenty stations were used for estimation of parameters for the Eurasian plate (blue color vectors). Two stations were used for the estimation of parameters for the African plate (red color vectors).

formed for three stations (7080, 7091, and 7105). Next, the stations were included one after another (7411, 1953, 7082, 7112, 7114, 7122, 7295, 7410, 7894, 7884), as shown in Figs. 7, 8, and 9. The stability of the estimated parameters and their errors became visible for about 5 stations. The final estimated values, $\Phi = -4.97° \pm 0.66°$, $\Lambda = 272.31° \pm 0.24°$, and $\omega/Ma = 0.183 \pm 0.004$, are given in Table 2. Two stations, Quincy no. 7109 and Monument Peak no. 7110, given in Fig. 6 were deleted from the solution, because of a systematic error of adjustment. Directions of displacement vectors for these stations do not agree with the plate motion parameters for the North American plate. For the Eurasian plate, the selected 25 SLR stations were investigated (Figs. 10 and 11), twenty stations are located in the European continent and five stations are located in the Asian continent. The first estimation was performed for three stations (1181, 7833, and 7834). Next, the stations were included one after another (7835, 7236, 7249, 7810, 7836,

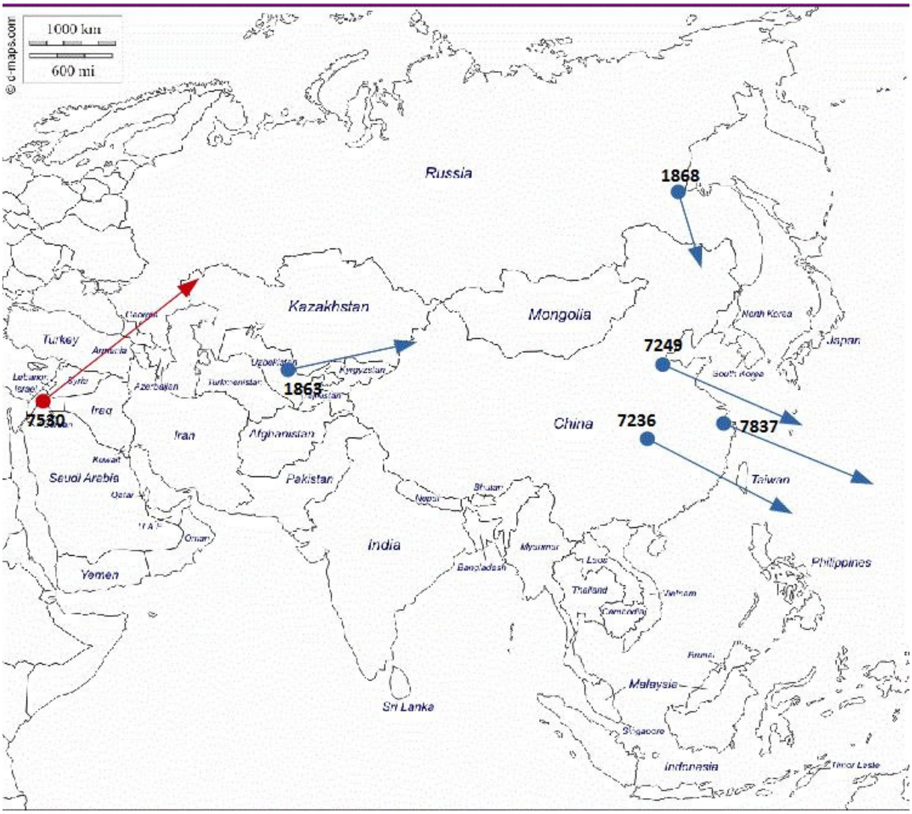

Fig. 11. Six station positions and velocity vectors located on the Asian plate. Five stations were used for parameter estimation of the Eurasian plate (blue color vectors). One station was used for parameter estimation of the African plate (red color vector).

7837, 7840, 7839, 7811, 7546, 7550, 7939, 7560, 7575, 7580, 7585, 7587, 1824, 1863, 1868, 1873, 7510); this is shown in Figs. 12, 13, and 14. The stability of the estimated parameters and their errors became visible for about 9 stations. The final estimated values, $\Phi = 56.20 \pm 0.56$, $\Lambda = 266.50 \pm 1.00$, and $\omega/Ma = 0.267 \pm 0.004$, are given in Table 3. Unfortunately, the number of stations which are localized in the Australian plate is very small (3 stations in the whole plate: no. 7843 Tidbinibilla, no. 7090 Yarragadee, and no. 7849 Yarragadee). In addition, for the two stations, nos. 7090 and 7849, the distance is equal to 37 km only. Because the minimum number of stations which is needed for estimation of the plate motion parameters is equal to 2, only one station more is used to the analysis, but the estimated errors are the smallest.

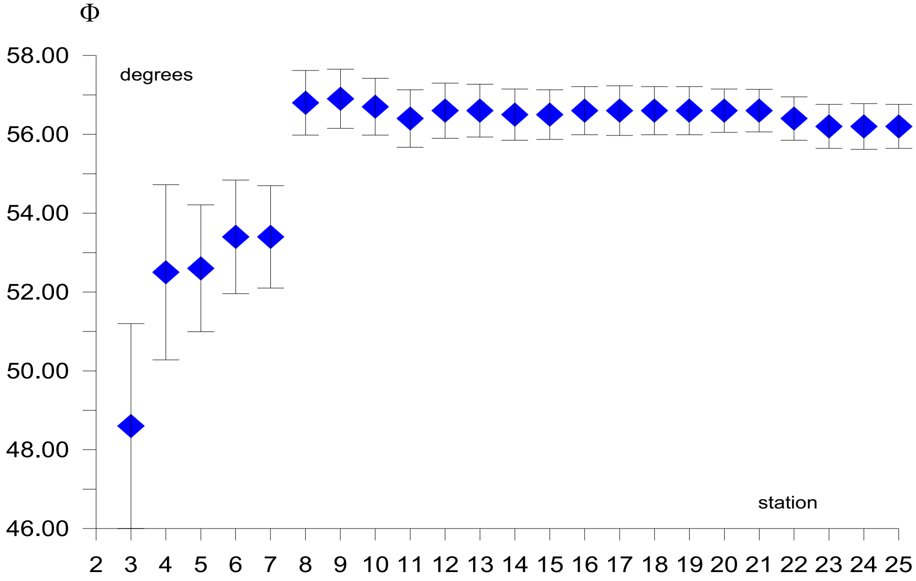

Fig. 12. Estimated parameter Φ and its error of the Eurasian plate motion for SLR network of 25 selected stations using the least square sequential solution.

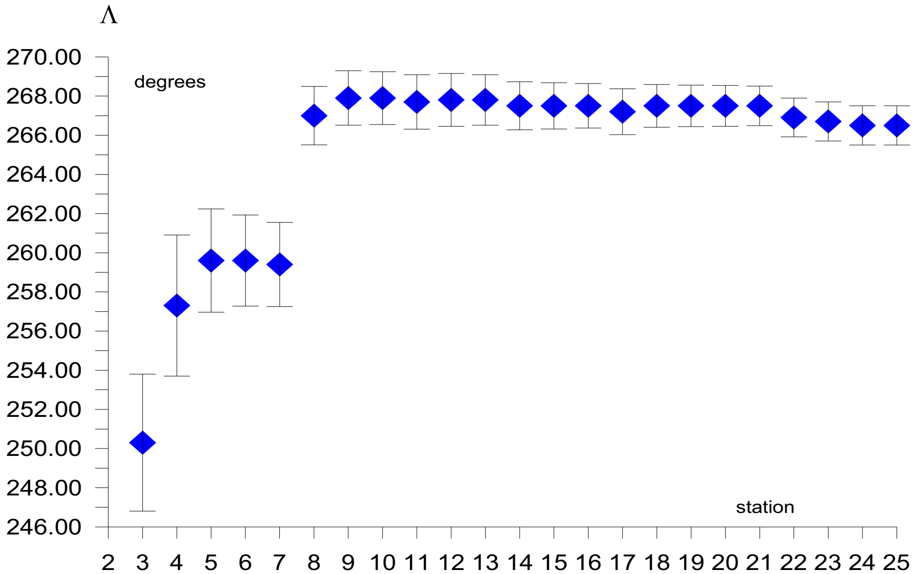

Fig. 13. Estimated parameter Λ and its error of the Eurasian plate motion for SLR network of 25 selected stations using the least squares sequential solution.

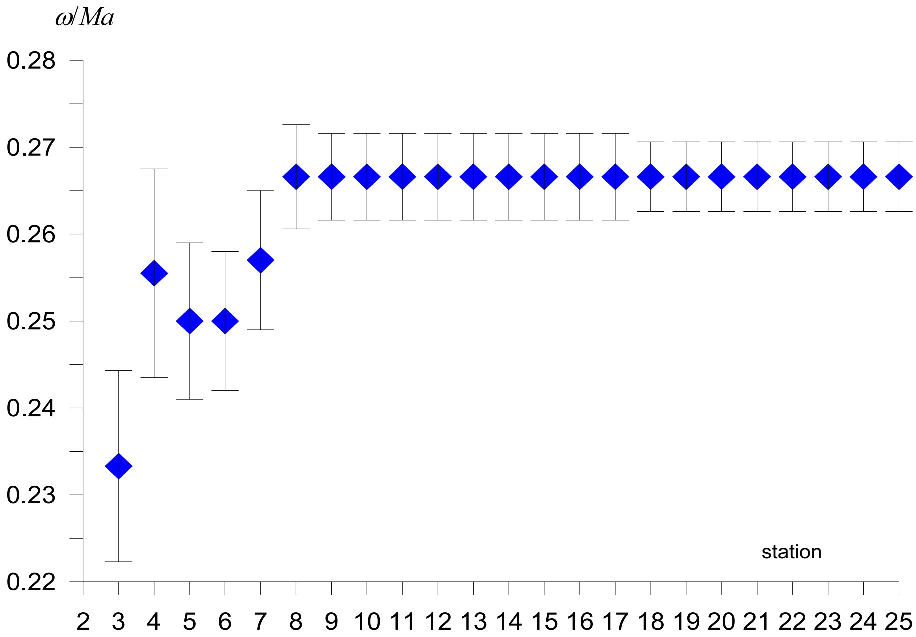

Fig. 14. Estimated parameter (ω/Ma) and its error of the Eurasian plate motion for SLR network of 25 selected stations using the least squares sequential solution.

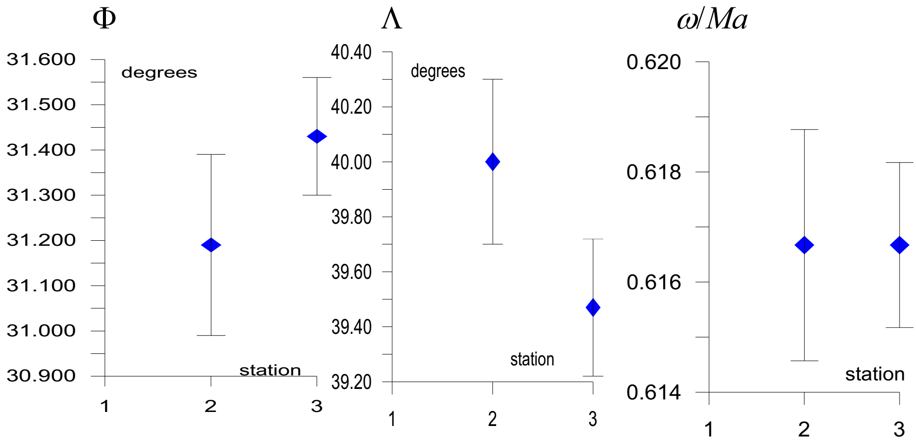

Fig. 15. Plate motion parameters (Φ, Λ, ω) for the Australian plate (first point for 7843 Tidbinibilla and 7090 Yarragadee, second point for 7843 Tidbinibilla + 7090 Yarragadee + 7849 Yarragadee).

Table 1

Estimated plate parameters and their error of the African plate motion for SLR network of 7 selected stations using the least squares sequential solution

AFRICAN PLATE Parameters of the tectonic plate displacement Ω (Φ, Λ, ω)				
No.	Name and number station	Φ [degrees]	Λ [degrees]	ω/*Ma*
2	Bar Giyyora 7530 + + Hartebeesthoek 7501	49.49 ± 1.34	257.65 ± 8.97	0.317 ± 0.059
3	+ Matera 7939	50.90 ± 0.27	272.00 ± 0.53	0.293 ± 0.021
4	+ Lampedusa 7544	50.95 ± 0.21	276.00 ± 0.42	0.283 ± 0.002
5	+ Helwan 7831	50.85 ± 0.36	277.72 ± 0.70	0.283 ± 0.003
6	+ Sutherland 7502	50.78 ± 0.24	277.48 ± 0.52	0.283 ± 0.002
7	+ Noto 7543	50.78 ± 0.22	277.48 ± 0.52	0.283 ± 0.002

Table 2

Estimated plate parameters and their error of the North American plate motion for SLR network of 13 selected stations using the least squares sequential solution

NORTH AMERICAN PLATE Parameters of the tectonic plate displacement Ω (Φ, Λ, ω)				
No.	Name and number station	Φ [degrees]	Λ [degrees]	ω/*Ma*
3	Fort Davis 7080+ + Westford 7091+ + Washington 7105	–8.20 ± 1.19	272.10 ± 0.42	0.167 ± 0.008
4	+ Richmond 7295	–4.73 ± 1.19	272.37 ± 0.42	0.167 ± 0.008
5	+ Mazatlan 7122	–4.86 ± 1.06	272.29 ± 0.38	0.167 ± 0.008
6	+ Algonguin 7410	–4.93 ± 1.02	272.71 ± 0.35	0.183 ± 0.007
7	+ Platteville 7112	–4.93 ± 0.87	272.71 ± 0.33	0.183 ± 0.006
8	+ Qwens Valley 7114	–4.95 ± 0.83	272.71 ± 0.29	0.183 ± 0.005
9	+ La Grande 7411	–4.95 ± 080	272.71 ± 0.27	0.183 ± 0.005
10	+ Santiago de Cuba 1953	–4.96 ± 0.77	272.71 ± 0.26	0.183 ± 0.005
11	+ Bear Lake 7082	–4.96 ± 0.72	272.71 ± 0.25	0.183 ± 0.004
12	+ Albuquerque 7884	–4.97 ± 0.69	272.71 ± 0.24	0.183 ± 0.004
13	+ Yuma 7894	–4.97 ± 0.66	272.71 ± 0.24	0.183 ± 0.004

Table 3

Estimated plate parameters and their error of the Eurasian plate motion for SLR network of 25 selected stations using the least squares sequential solution

EURASIAN PLATE Parameters of the tectonic plate displacement Ω (Φ, Λ, ω)				
No.	Name and number station	Φ [degrees]	Λ [degrees]	ω/Ma
3	Potsdam 1181 + + Kootwijk 7833 + + Wettzell 7834	48.60 ± 2.60	250.30 ± 3.50	0.233 ± 0.011
4	+ Grasse 7835	52.50 ± 2.22	257.30 ± 3.60	0.256 ± 0.012
5	+ Wuhan 7236	52.60 ± 1.61	259.60 ± 2.64	0.250 ± 0.009
6	+ Beijing 7249	53.40 ± 1.44	259.60 ± 2.33	0.250 ± 0.008
7	+ Zimmervald 7810	53.40 ± 1.30	259.40 ± 2.15	0.250 ± 0.008
8	+ Potsdam 7836	56.80 ± 0.82	267.00 ± 1.49	0.267 ± 0.006
9	+ Shanghai 7837	56.90 ± 0.75	267.90 ± 1.39	0.267 ± 0.005
10	+ Herstmonceux 7840	56.70 ± 0.72	267.90 ± 1.35	0.267 ± 0.005
11	+ Graz 7839	56.40 ± 0.73	267.70 ± 1.39	0.267 ± 0.005
12	+ Borowiec 7811	56.60 ± 0.70	267.80 ± 1.35	0.267 ± 0.005
13	+ Medicina 7546	56.60 ± 0.67	267.80 ± 1.29	0.267 ± 0.005
14	+ Trieste 7550	56.50 ± 0.65	267.50 ± 1.23	0.267 ± 0.005
15	+ Matera 7939	56.50 ± 0.63	267.50 ± 1.18	0.267 ± 0.005
16	+ Riga 7560	56.60 ± 0.61	267.50 ± 1.14	0.267 ± 0.005
17	+ Diarbakir 7575	56.60 ± 0.63	267.20 ± 1.17	0.267 ± 0.005
18	+ Melengiclick 7580	56.60 ± 0.61	267.50 ± 1.09	0.267 ± 0.004
19	+ Yozgat 7585	56.60 ± 0.61	267.50 ± 1.06	0.267 ± 0.004
20	+ Yiglica 7587	56.60 ± 0.55	267.50 ± 1.04	0.267 ± 0.004
21	+ Kiev 1824	56.60 ± 0.54	267.50 ± 1.01	0.267 ± 0.004
22	+ Maidanak 1863	56.40 ± 0.55	266.90 ± 0.99	0.267 ± 0.004
23	+ Komsomolsk 1868	56.20 ± 0.56	266.70 ± 1.00	0.267 ± 0.004
24	+ Simeiz 1873	56.20 ± 0.58	266.50 ± 1.00	0.267 ± 0.004
25	+ Askites 7510	56.20 ± 0.56	266.50 ± 0.99	0.267 ± 0.004

The final estimated values for the Australian plate, based on three stations only localized on the plate's surface, are $\Phi = 31.42° \pm 0.13°$, $\Lambda = 39.48° \pm 0.25°$, $\omega/Ma = 0.617 \pm 0.002$. A large concurrence of estimated parameters for SLR technique and model APKIM 2005 IGN can be seen in spite of the small number of SLR stations for the Australian plate. Maximum differences are of the order of 2 degrees. Stability of Australian plate motion parameters is shown in Fig. 15.

Table 4

Tectonic plate parameters estimated for the selected four plates for SLR stations in ITRF2008

Estimated parameters of the tectonic plate based on ITRF2008 model station velocities					Parameters of the tectonic plate
	Plate	Φ [degrees]	Λ [degrees]	ω/Ma [degrees/ million years]	Model APKIM 2005 IGN $\vec{\Omega}(\Phi, \Lambda, \omega / Ma)$ [degrees]
25	Eurasian	56.20 ± 0.56	266.50 ± 1.00	0.267 ± 0.004	53.4 ± 0.4, 264.3 ± 0.5, 0.259 ± 0.001
7	African	50.78 ± 0.22	277.48 ± 0.52	0.283 ± 0.002	48.1 ± 0.3, 280.7 ± 0.8, 0.279 ± 0.002
13	N. American	-4.97 ± 0.66	272.71 ± 0.24	0.183 ± 0.004	-4.3 ± 0.6, 275.8 ± 0.2, 0.194 ± 0.002
4	Australian	31.42 ± 0.13	39.48 ± 0.25	0.617 ± 0.002	32.8 ± 0.1, 36.7 ± 0.3, 0.639 ± 0.002

Table 5

Comparison of our solution with the solution of Altamimi *et al.* (2011)

Estimated parameters of the tectonic plate based on ITRF2008 model station velocities			Model ITRF2008 Absolute plate rotation poles (Altamimi *et al.* 2011)
	Plate	ω_x, ω_y, ω_z (mas/a)	ω_x, ω_y, ω_z (mas/a)
25	Eurasian	-0.034 ± 0.005, -0.552 ± 0.007, 0.828 ± 0.005	-0.083 ± 0.008, -0.534 ± 0.007, 0.750 ± 0.008
7	African	-0.028 ± 0.005, -0.664 ± 0.004, 0.815 ± 0.004	no details
13	N. American	0.033 ± 0.009, -0.684 ± 0.006, -0.597 ± 0.009	0.035 ± 0.008, -0.662 ± 0.009, -0.100 ± 0.008
4	Australian	1.490 ± 0.004, 1.226 ± 0.008, 1.179 ± 0.007	1.504 ± 0.007, 1.172 ± 0.007, 1.228 ± 0.007

The final estimated values of the plate motion parameters for Eurasian, African, North American, and Australian plates are given in Table 4 and compared with Drewes (2009) solution (model APKIM 2005 IGN).

The angular velocities (ω_x, ω_y, ω_z) estimated from expression 2 in our analysis were compared with the solution of Altamimi *et al.* (2011). The great agreement between these solutions is shown in Table 5.

The computation was performed using FORTRAN 90 software called TPMSM (Tectonic Plate Motion by Satellite Method).

4. CONCLUSIONS

On the basis of the performed analysis, the following conclusions can be drawn:

- A remarkable concurrence of the estimated parameters (Φ, Λ, ω) for SLR technique and model APKIM 2005 IGN can be seen (Table 4) in spite of a small number of SLR stations located on the Earth's surface. The maximum differences are of the order of 2 degrees.
- Generally, stabilization of estimated tectonic plate parameters and their random distribution of errors for about 7-8 stations situated on each plate can be noticed. As an example, the Eurasian, North American, and African plates were taken into consideration. For a greater number of stations, changes of parameter values are smaller than the value of error.
- For the Australian plate with three stations only, the stability of the tectonic plate parameter estimation cannot be adjusted using the sequential method. The number of located stations is not sufficient for analysing the solution stability. It is recommended to increase the number of stations on the Australian plate. Despite this fact, the estimated errors of plate motion parameters are very small, probably because this plate is young, not cracked along plate boundary, and on the plate's surface there is not observed any old tectonic fold of a mountain range. But it is recommended to increase the number of stations on the Australian plate for many scientific tasks.
- The result may not be representative for the entire interior of the plates, particularly for the plates' boundaries. This can be seen for stations of controversial location, such as Quincy no. 7109 and Monument Peak no. 7110, located in the North American continent in plate's boundary, in a region of strong tectonic activity. The sequential method allows detection of stations with their own motion inconsistent with the motion of the whole plate. This will be described in detail in the next paper.
- Continuous monitoring of station displacement is recommended, particularly for stations located in micro plates and plates' boundaries. For these

stations, velocities should be treated as unknown in the solution. An example for this is station Monument Peak no. 7110.

- Generally, regular distribution of station positions is recommended for each tectonic plate; concentration of a high number of stations in a small area does not cause an increase of solution accuracy.

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