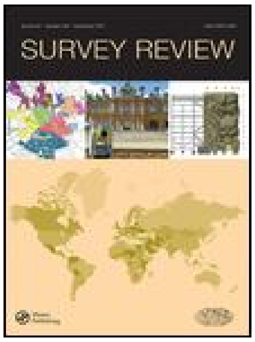

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Evaluation of the GSRM2.1 and the NUVEL1-A values in Europe using SLR and VLBI based geodetic velocity fields

Mina Rahmani[1], Vahab Nafisi [1], Sigrid Böhm [2] and Jamal Asgari [*1]

The NUVEL1-A is one of the old and popular plate tectonic models. While the NUVEL1-A is a geological-based model, recently a model has been proposed (GSRM2.1 model) which is based on the results of space geodetic techniques. In this work, we investigate the consistency of these models with the VLBI and SLR results in Europe. Direction and magnitude of the horizontal motion from NUVEL-1A and GSRM2.1 models are compared with corresponding values from both geodetic techniques. This comparison provides valuable deductions such as: (1) The values of geodetic-based model (GSRM2.1) show better agreement with SLR and VLBI results (2) In each comparison between geodetic results and modelled values, direction divergence is larger than magnitude difference.

Keywords: Velocity field, SLR, European geodetic VLBI network, NUVEL-1A, GSRM2.1, Plate tectonic motion

1. Introduction

Nowadays space geodetic techniques such as SLR (Satellite Laser Ranging; Alothman and Schillak 2014), VLBI (Very long Baseline Interferometry; Schuh and Behrend 2012), and GPS (Global Positioning System; Nilforoushan *et al.* 2003) can provide position and velocity of points on the Earth's surface with high accuracy, consequently, the shape deformation of Earth can be precisely investigated using these techniques.

Several geodynamical researches have been fulfilled using SLR missions. In the following, some of these researches and the obtained conclusions will be remarked/mentioned.

The first results of the baseline change monitoring deduced from the BEACON EXPLORER SLR mission (which was launched in 1964) were represented by Smith *et al.* (1979). The results showed that the baseline between two sites in California decreased with the rate larger than it had been reported by Minster and Jordan (1978) based on the geological evidence.

LAGEOS (LAser GEOdynamic Satellite) was fired to space in 1976 by NASA (National Aeronautics and Space Administration), after that on October 22, 1992, the Italian Space Agency launched LAGEOS-2 in cooperation with NASA. These two missions provide the opportunity to improve the measurement of the range in the SLR technique. Valuable information including Earth rotation, polar motion, temporal variation of a point position on the Earth's surface, and tectonic plate motion parameters can be derived from both LAGEOS missions (Biancale *et al.* 1991, Gegout and Cazenave 1991).

Several studies were carried out to investigate crustal deformation using the LAGEOS missions: (1) Christodoulidis *et al.* (1985) have announced that the obtained accuracy from LAGEOS laser data, from January 1979 to the end of 1982, is in the level of required accuracy in geophysics. (2) Smith *et al.* (1990) have reported that the LAGEOS-derived velocities of 22 SLR stations (which are situated on 7 major tectonic plates) deduced from 1978 to 1988 LAGEOS data are in agreement with geological knowledge (NUVEL1-A model) and VLBI results. (3) In order to monitor the effect of tectonic motion on station positions, a comparison has been done between the horizontal component of relative velocities of each couple of stations, which are located on different tectonic plates, and the NUVEL-1 model by Biancale *et al.* (1991). The results represented good consistency between the satellite and geological solution for the stations far from the plate boundaries, while in case of sites located near the plate boundary some discrepancies were detected.

Although most of the previous studies were conducted using the LAGEOS missions, for the first time Ajisai (launched in 1986) SLR data were utilised for the TRF (Terrestrial Reference Frame) determination by Sengoku (1998). To do this, the author analysed eight years of Ajisai SLR data. The rate of baseline changes was in good agreement with the result of LAGEOS, NUVEL1-A, and ITFR93 (International Terrestrial Reference Frame 1993), except for sites approaching plate boundaries, in which significant divergences from the geological plate motion model were recognised.

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For the first time, VLBI technique was introduced within the mid-1960 by Matveenko *et al.* (1965). While at first, the astronomical application of this technique was widely accepted, later scientists figured out the potential of this technique in the geodetic and geodynamic science (Shapiro and Knight 1970, Sovers *et al.* 1998, Petrov *et al.* 2009, Schuh and Behrend 2012).

The European Geodetic VLBI network was established in January 1990 to determine surface deformation in Europe and estimate reliable reference frames for other space geodesy techniques available in this region, especially GPS technique (Campbell *et al.* 1993, Haas *et al.* 2003).

Although the distribution of VLBI and SLR stations over the globe, particularly in the southern hemisphere, is limited, a good density can be found in Europe. So far, numerous geodynamics researches have been done in Europe using the European Geodetic VLBI network (e.g. Ward 1990, Campbell *et al.* 1993, Campbell and Nothnagel 2000, Haas *et al.* 2000, Haas *et al.* 2002, Haas *et al.* 2003, Vennebusch 2003, Sarti *et al.* 2011, Krásná *et al.* 2013); it is worth to mention that in all the referenced studies, the processed data were basically the same but the covered time duration, number of the involved VLBI stations, the used software, and approaches were different.

Besides the geodetic-derived Earth motion which is directly measured, crustal deformation values can be theoretically predicated by different models. In the following some of these models are listed: NUVEL1 (Argus and Gordon 1991), NUVEL1-A (DeMets *et al.* 1994), ITRF2000 (Drewes and Angermann 2001), MORVEL (DeMets *et al.* 2010), ITRF2008 (Altamimi *et al.* 2012), GSRMv2.1 (Kreemer *et al.* 2014), ITRF2014 (Altamimi *et al.* 2016).

This paper is devoted to the comparison of VLBI, and SLR velocity field results from NUVEL1-A and GSRM2.1 model in Europe. The older selected model (NUVEL1-A) is a geological-based model, while the newer one (GSRM2.1) has been built using GPS-derived velocities; i.e. with considering these models, not only we can compare geological-based results with geodetic-based ones, but also the improvement of model values can be realised. However, we present results based on the analysis of nearly 10-year data of the European geodetic VLBI network, covering January 2008 to July 2017 in a first step (Sect.4.1). Then, in a second step, velocities of SLR stations, which are derived from the coordinate time-series of SLR stations with monthly time resolution and spectral analysis, will be provided (Sect.4.2). In order to have a reliable and logical comparison, coordinate time-series of SLR stations span the same time period as VLBI observations (2008–2017). In each step, the magnitude and direction of the horizontal motion of current geodetic results are compared with two tectonic plate motion models, NUVEL-1A and GSRM2.1. Finally, in Sect.5, the mean of the absolute value of the differences of magnitude and direction between the new geodetic results and the NUVEL1-A and the GSRM2.1 predicted values are reported. Furthermore, differences of direction and magnitude of horizontal motion between geodetic results and values from the mentioned models are studied at VLBI stations co-located with SLR sites.

2. European geodetic VLBI network and VLBI analysis

Table 1 lists European VLBI sites with their associated ellipsoidal coordinates, IVS (the International VLBI Service for Geodesy and Astronomy) Code, radio telescope diameter, and relevant country.

IVS coordinated VLBI sessions are categorised into several types that vary in terms of start times, participating stations, session purposes, etc. Among different types of VLBI sessions with various codes, the purpose of the 'EUROPE' code is the determination of the station coordinates and their time variation in the European geodetic VLBI network. As said before, in this paper we want to investigate the velocity field of Europe, hence, 55 European VLBI sessions (from January 2008 to July 2017, EUROPE-91 to EUROPE-146) are gathered. Figure 1 reveals the number of European VLBI sessions per sites in the European geodetic VLBI network. Although 15 stations took part in these sessions, to provide the reliable observation length for velocity determination, WETTZ13N (Wn) is ignored. Figure 2 demonstrates the final distribution of the VLBI sites in this work.

The European VLBI sessions were processed to compute coordinates and velocities of the stations using VieVS (Vienna VLBI and Satellite software; Böhm *et al.* 2018). VieVS has been developed since 2008 at the Department of Geodesy and Geoinformation of TU Wien (Krásná *et al.* 2013). The collected VLBI sessions were processed without considerable change in the default settings of VieVS, so that the station coordinates and velocities were determined by applying the two principal conditions (No-Net-Translation (NNT) and no-net-rotation (NNR)) on ITRF2014. In addition to the atmospheric loading (Petrov and Boy 2003) and the effect of thermal deformation of the radio telescope, tidal ocean loading (Scherneck 1991) was considered in the data processing based on FES2004 (Lyard *et al.* 2006). The Ionosphere correction was carried out using NGS file information/content. ICRF2 (the 2nd International Celestial Reference Frame) (Ma *et al.* 2009) was regarded as the accurate coordinates of radio sources; therefore, it was possible to determine VLBI station coordinates and baseline length precisely. A simple outlier test was applied for detecting and omitting bad outliers, considering all cut-off angle observations.

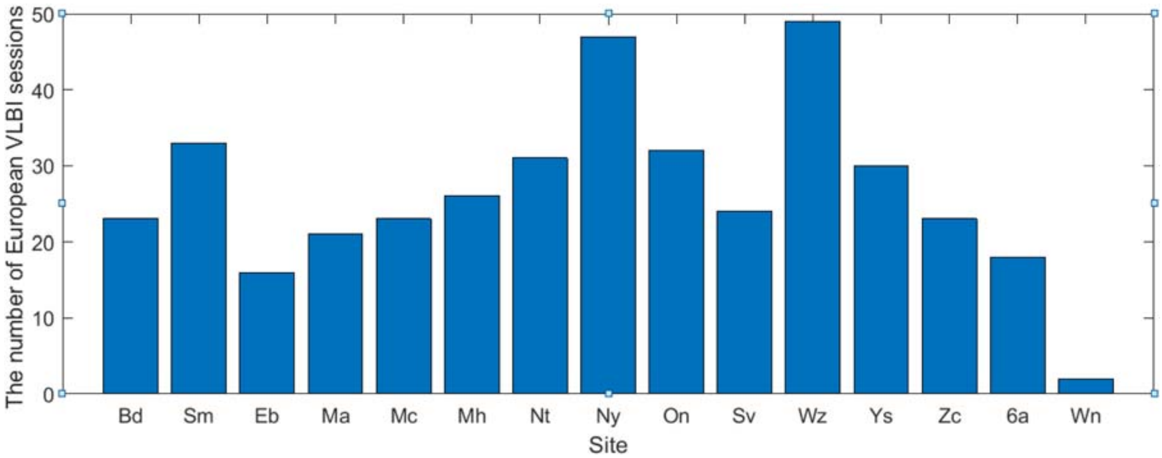
Five Earth orientation parameters (x-pol, y-pol, dUT1, dX, and dY) were estimated once each session using the IERS EOP14 C04.* (Earth Orientation Parameters14 C04 provided by International Earth Rotation and Reference System) series as the initial values. In addition to a quadratic clock polynomial, relative clock parameters were estimated per hour and with respect to an introduced reference clock in each session. Moreover, atmospheric zenith wet delays were estimated in an hour interval using the VMF1 (Vienna Mapping Functions; Böhm *et al.* 2006). Finally, north and east gradients were estimated per six hours.

According to Fig. 3, the a posteriori variance factor (χ^2) of all processed sessions, are less than 1.5, for more information about this parameter refer to Krásná *et al.* (2013). To achieve this threshold, in several sessions it

*https://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html.

Table 1 European VLBI sites, size of the telescope, IVS code, and relevant/related country

Site	IVS Code	Diameter (m)	Lat. (Deg.)	Log. (Deg.)	Country
Badary	Bd	32	51.77	102.23	Russia
Crimea	Sm	22	44.40	33.98	Ukraine
EFLSBERG	Eb	100	50.52	6.88	Germany
Matera	Ma	20	40.65	16.70	Italy
Medicina	Mc	32	44.52	11.56	Italy
Metsahovi	Mh	14	60.22	24.39	Finland
Noto	Nt	32	36.88	14.99	Italy
Ny-Alesund	Ny	20	78.93	11.87	Norway
Onsala	On	20	57.40	11.93	Sweden
Svetloe	Sv	32	60.53	29.78	Russia
Wettzell	Wz	20	49.15	12.88	Germany
Yebes40m	Ys	40	40.52	356.91	Spain
Zelenchukskaya	Zc	32	43.79	41.57	Russia
Madrid(DSS65A)	6a	34	40.43	355.75	Spain



1 The number of European VLBI sessions per sites

was necessary to consider some additional issues, as an illustration, clock break, bad stations, or bad baselines. Accessing this threshold proves that the processed sessions are in good quality.

After the session-wise processing, a new TRF was determined using the 'VIE_GLOB' module of VieVS. This module can provide common parameters between different sessions by combining the normal equation systems (Krásná *et al.* 2014). The contribution of different stations in the TRF determination can be inferred from Fig. 4, a graphical output of the GLOBAL SOLUTION menu.

3. SLR data analysis

Figure 5 represents SLR station distribution in this work.

Coordinates time-series of SLR stations were gathered for the time period 2008–2017[†] on monthly temporal resolution. Each star in Fig. 6 represents the availability of per-site coordinates each year (the mark of each year is plotted when at least coordinates of one month in the relevant year are available). Almost at all stations (with exception RIGL) a continuous time-series can be inferred from Fig. 6. LVIL station is excluded because the covered time span is too short (according to Fig. 6).

Only coordinates at the 95% confidence level were involved. Furthermore, the time series of all stations were investigated in terms of abrupt changes/shift and jump. To determine the geocentric velocity of per-site, a mean value for X, Y, and Z components was subtracted from the collected coordinates of the related site. Afterwards, the offset (a_0) and rate (r) of linear regression, annual (a_1, b_1), and semi-annual (a_2, b_2) components of each station coordinates time-series were estimated using the least-squares adjustment (Amiri-Simkooei 2007):

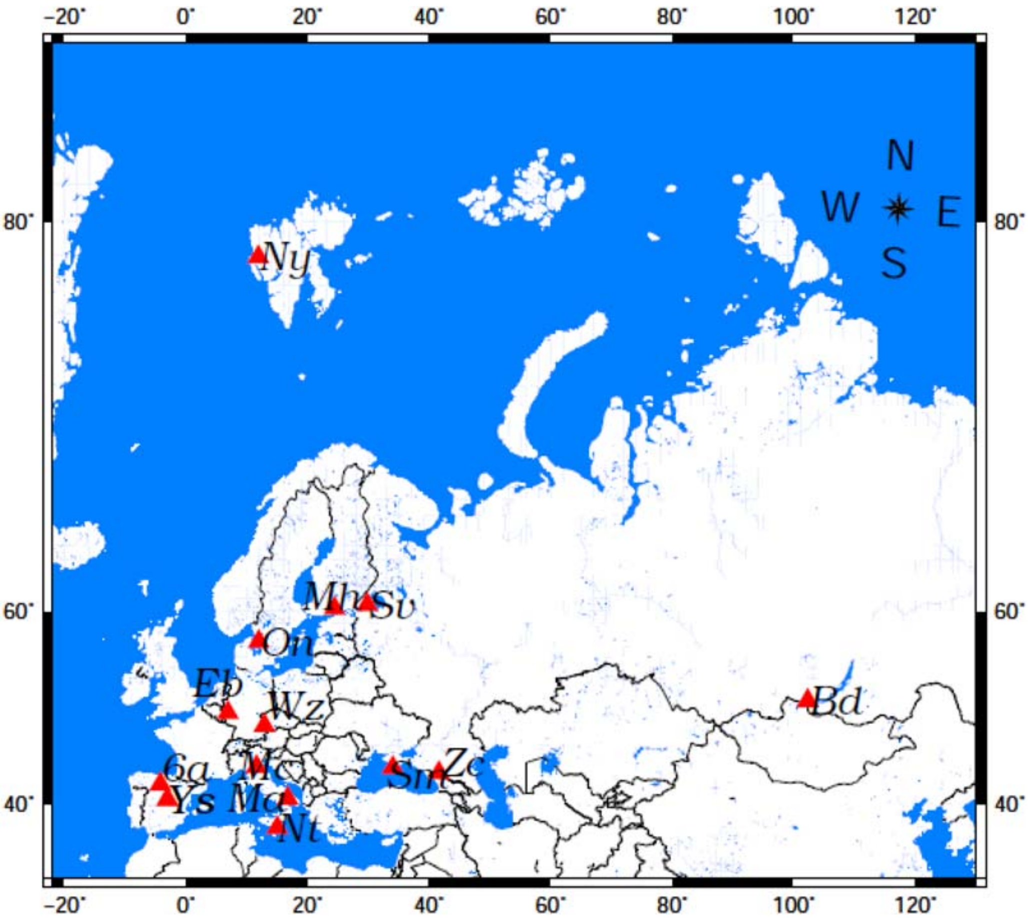
$$x_{\text{cap}} = \begin{bmatrix} a_0 \\ r \\ a_1 \\ b_1 \\ a_2 \\ b_2 \end{bmatrix} = (A^T Q_y^{-1} A)^{-1} A^T Q_y^{-1} y \qquad (1)$$

where the corresponding row of the ith time epoch in the design matrix was defined:

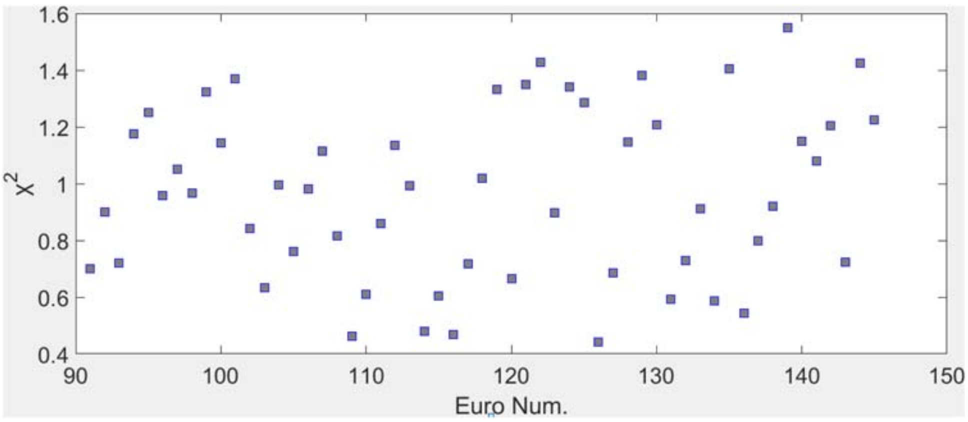
$$A(i,:) = [1\ t_i \cos 2\pi t_i\ \sin 2\pi t_i \cos 4\pi t_i\ \sin 4\pi t_i]; \qquad (2)$$

Besides, standard deviations of the estimated parameters were derived from the variance-covariance

[†]https://cddis.nasa.gov/archive/slr.



2 Distribution of European geodetic VLBI stations used in this paper



3 The a posteriori variance factor (χ^2) of the processed sessions

matrix which was estimated from the following equation:

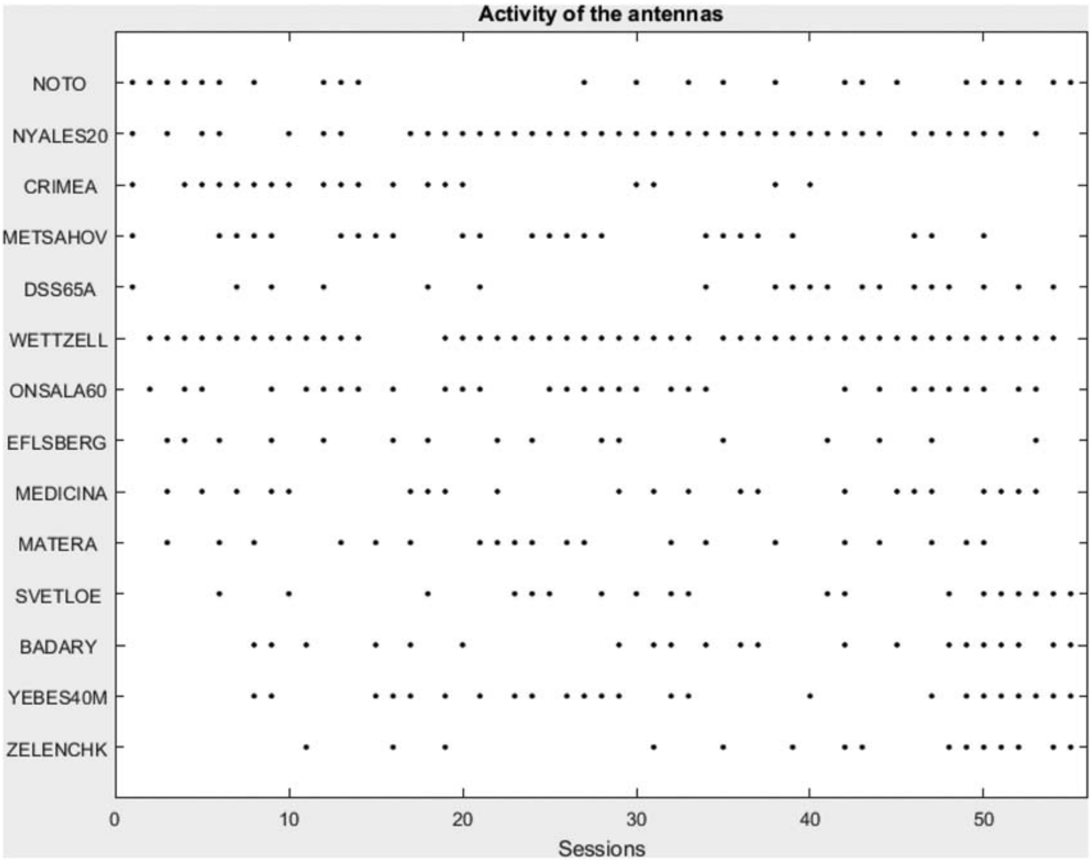
$$Q_{x\,\mathrm{cap}} = (A^T Q_y^{-1} A)^{-1} \tag{3}$$

4. Results and discussion

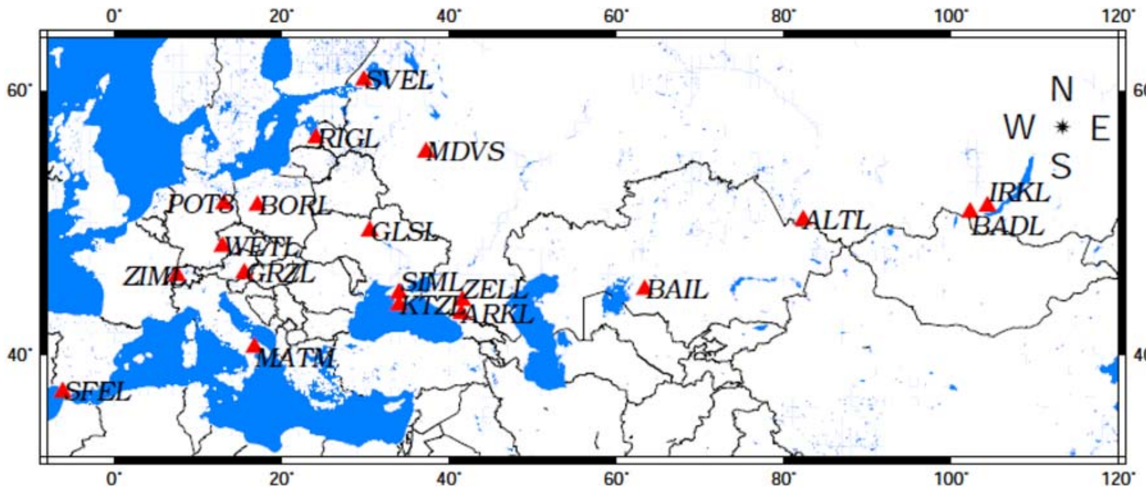
4.1 VLBI velocity field

Estimated Cartesian velocities were transferred into the topocentric coordinate system (Matev 2011), Table 2. As shown in Table 2, the CRIMEA(Sm) station formal errors (in all three velocity components) are larger than 1 mm/yr., while velocities of all other stations (both horizontal and vertical components) have formal errors less than 1 mm/yr. The reason for the obtained large formal errors at Sm station is the big gaps in the contribution of this site in the TRF determination using the GLOBAL SOLUTION menu, this could be inferred from the Fig. 4.

In the next step, the horizontal components of the obtained velocities were compared with the NUVEL-1A and the GSRM2.1 plate tectonics model (Fig. 7). In this paper, the modelled velocities were acquired from the UNAVCO (University NAVSTAR Consortium) Plate Motion Calculator.[‡]



4 Participation of VLBI stations in the TRF determination using the GLOBAL SOLUTION menu



5 The SLR station locations

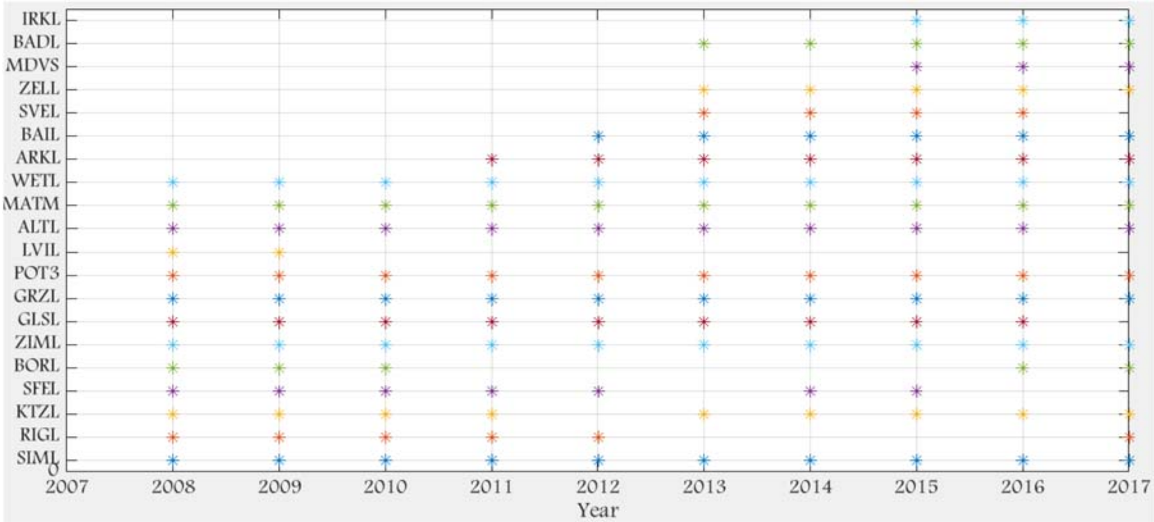
Figure 7 illustrates a comparison between velocities obtained from VLBI (green arrows) and modelled velocities from NUVEL-1A (brown arrows) and GSRM2.1 (red arrows) model.

As illustrated in Fig. 7, Eurasia's motion in Europe is in north-east direction with a maximum velocity up to about 30 mm/yr. (MATERA station), whereas the azimuth approximately reached 142.4445 degrees in the eastern part of this plate (with consideration of BADARY station).

In the following, first, the horizontal motion deduced from VLBI will be compared with GSRM2.1 model values, and then a comparison will be carried out between our VLBI-derived results and the geological-based model values (NUVEL1-A).

The absolute differences of magnitude and direction of the estimated velocities with respect to GSRM2.1 are shown in Fig. 8. It is evident that almost at all stations estimated velocities are smaller than values predicted by

‡https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html.



6 The availability of SLR coordinates time-series for the period 2008–2017

Table 2 Computed velocities and their corresponding formal errors

Station name	V_e (mm/yr.)	V_n (mm/yr.)	V_{Up} (mm/yr.)	Magnitude of horizontal motion
BADARY	27.06±0.20	−7.19±0.20	−0.32±0.20	28.00
CRIMEA	24.27±1.83	11.56±1.26	3.49±1.83	26.88
EFLSBERG	17.45±0.44	16.02±0.20	−3.22±0.46	23.69
MATERA	24.10±0.24	19.43±0.12	1.17±0.25	30.96
MEDICINA	21.89±0.25	18.23±0.10	−3.42±0.25	28.49
METSAHOV	18.84±0.53	13.74±0.34	0.32±0.65	23.32
NOTO	22.20±0.46	20.05±0.21	1.77±0.43	29.92
NYALES20	8.45±0.42	16.24±0.40	2.83±0.88	18.30
ONSALA60	15.87±0.32	15.33±0.20	0.41±0.37	22.06
SVETLOE	20.84±0.34	12.86±0.22	7.66±0.45	24.49
WETTZELL	19.65±0.19	15.85±0.10	−1.94±0.19	25.24
YEBES40M	18.58±0.29	14.96±0.20	4.35±0.29	23.86
ZELENCHK	25.55±0.89	11.89±0.50	5.94±0.87	28.18
DSS65A	17.96±0.49	15.09±0.20	−1.97±0.49	23.46

Notes: V_e, V_n , V_u, indicate motion in east, north, and up direction, respectively. All values are presented in mm/yr.

the GSRM2.1 model. Inconsistencies, in terms of both magnitude and direction, in the northern part of the Mediterranean Sea (Ma site) are larger than in other parts of the network; the complicated tectonic structure in this region can be considered as the reason for this mismatch. It is worth mentioning that unlike the ignorable magnitude differences between the geodetic velocity and GSRM2.1 model at Badary (Bd) and NYALES20 (Ny), difference between the azimuth of the estimated velocities and the predicted ones is rather large and considerable. WETTZELL (Wz), which is located in the central part of Europe, is the site fitting best; which means that the GSRM2.1 model can predict horizontal motion in central Europe better than in other parts. Krásná *et al.* (2013) introduced this part of Europe as a tectonically stable region, it seems this stability can be regarded as the reason for the resulting agreement between geodetic and modelled results at WETTZELL.

To summerise our results reveal that almost all stations, magnitude and azimuth differences between the VLBI and GSRM2.1 model are smaller than 5 mm/yr and 5 degrees, respectively.

The following results can be deduced from the comparison between VLBI-derived results and NUVEL1-A model values (Fig. 9): (1) almost at all stations magnitude differences between the VLBI results and NUVEL1-A predicted values are smaller 5 mm/yr., expect for Mc and On sites (Onsala). (2) Despite the small magnitude difference at NYALES20 (Ny), the largest azimuth mismatch belongs to this site; it implies that postglacial rebound mostly affects the direction of horizontal motion rather than the magnitude. (3) Despite the small magnitude differences at Wz and Eb sites (central part of Europe), noticeable direction discrepancies are recognised at these sites. (4) Good agreement is observed at Ys and 6a sites (sites in the western part of Mediterranean Sea) in terms of both direction and magnitude.

The average differences between our results and NUVEL-1A are 1.14 mm/yr and −5.60 degree in magnitude and direction; i.e. at most sites, the directions of the computed velocities are smaller than the modelled values in NUVEL1-A while the magnitudes are larger. In a previous article, Krásná *et al.* (2013) compared the European Geodetic VLBI network results with the NUVEL1-A model. They analysed VLBI data from 1990 to 2011. Subsequently, they stated 1.51 mm/yr and −5.81 degree as the differences of the magnitude and direction between the geodetic results and predicted values, refer to Table 3. It can be understand from

7 The map of comparison between VLBI-deduced velocities and the modelled velocities from NUVEL-1A and GSRM2.1. Ellipses are at 95% confidence level. Brown, red, and green arrows indicate NUVEL-1A, GSRM2.1, and geodetic velocities, respectively

Table 3 that during the years, differences between the VLBI results and NUVEL1-A values get smaller. The use of newer observations, improvement of software and VLBI radio telescope hardware, updated initial values in VieVS such as ITRF 2014 and IERS EOP 14 C04 instead of VTRF2008 (VieVS TRF2008) and IERS EOP 08 C04 (that was used by Krásná *et al.* (2013)), etc. can be reasons for this change.

4.2 SLR velocity field

Eventually, the computed Cartesian velocities were transferred into the topocentric coordinate system. Estimated velocities and their corresponding formal error are provided in Table 4. Table 4 shows that all three components of MDVS (1874) and IRKL (1891) velocities have formal errors larger than 1 mm/yr. (this low accuracy could be explained by their short period of time). However, the formal errors of all other stations (three components) are less than 1 mm/yr. SLR-derived velocity field shows that the maximum value of horizontal motion in Europe is approximately 30 mm/yr. (Table 4), in agreement with the VLBI results.

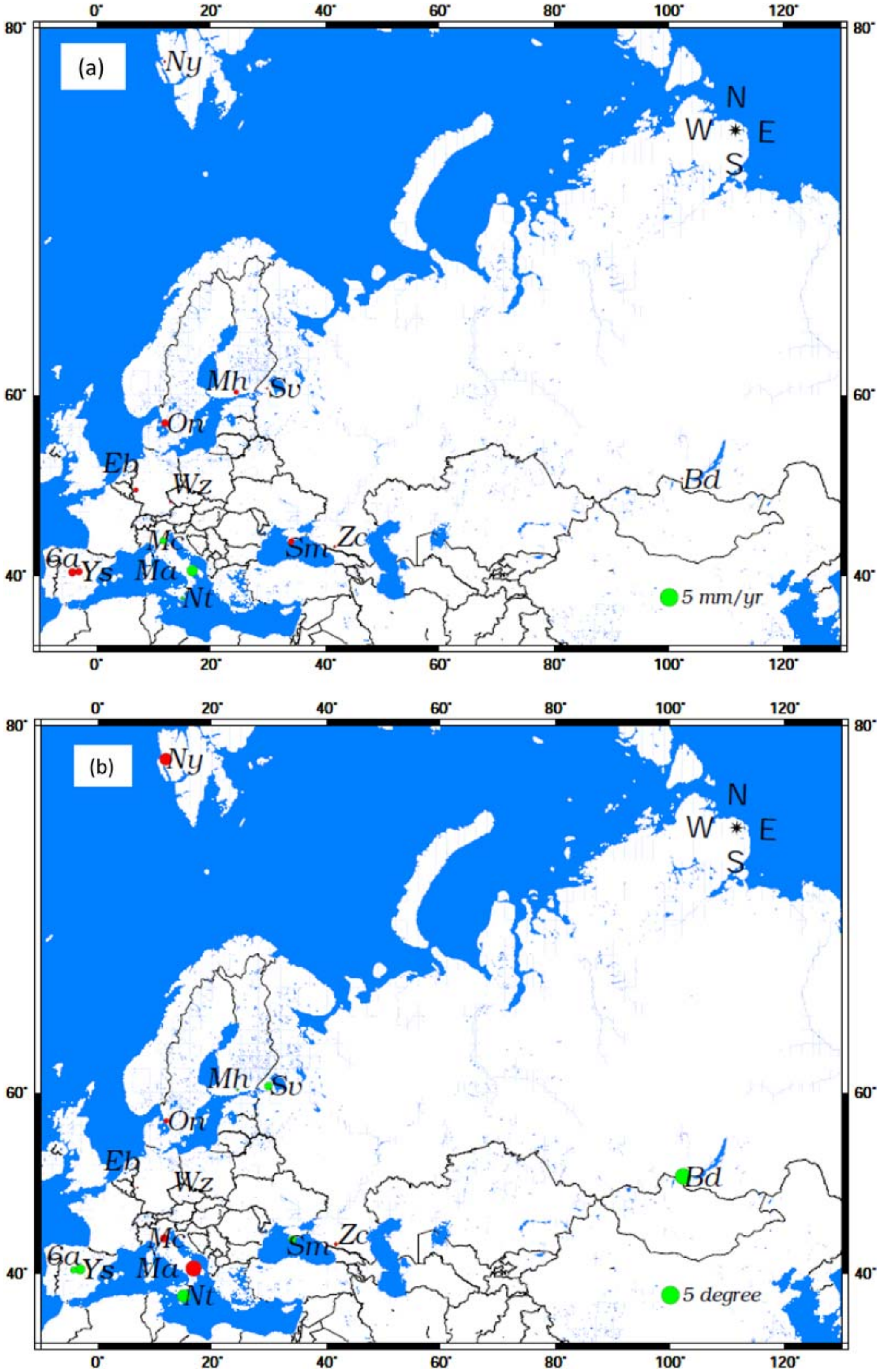
In the following, the horizontal component of estimated velocities will be compared with GSRM2.1 and NUVEL-1A model. Figure 10 is a graphical report of this comparison.

Figure 10 suggests that the Eurasian plate motion direction in Europe is north-east. Also, both estimated and modelled velocity fields depict a clockwise rotation in the Eurasian plate. Both mentioned results (the clockwise rotation and north-east motion in Europe) could be inferred from the VLBI-derived velocity field too, keeping in mind the fact that the SLR network has better spatial distribution than the European geodetic VLBI network.

The absolute differences of magnitude and direction of the horizontal motion between SLR-deduced velocities and the modelled values from GSRM2.1 are illustrated in Fig. 11. Figure 11 can be interpreted as follows: inconsistencies, both in terms of direction and magnitude, in the central part of Europe are less than in other parts of this region. Almost at all stations magnitude differences between the SLR results and GSRM2.1 model are smaller than 5 mm/yr., except for sites located in the northern part of the Black Sea (KTZL and SIML). Moreover, considerable direction divergence are detected in the northern part of the Black Sea (KTZL and SIML). Finally, almost at all stations located in the central part of Europe, the estimated directions are larger than associated model values.

In the following, the magnitude and direction of SLR estimated velocities are compared with the corresponding NUVEL1-A predicted values (Fig. 12).

From Fig. 12, it is apparent that almost at all stations magnitude and direction of the estimated velocities are larger and smaller, respectively, than associated NUVEL1-A model predictions. The magnitude and direction of the estimated velocities in the central part

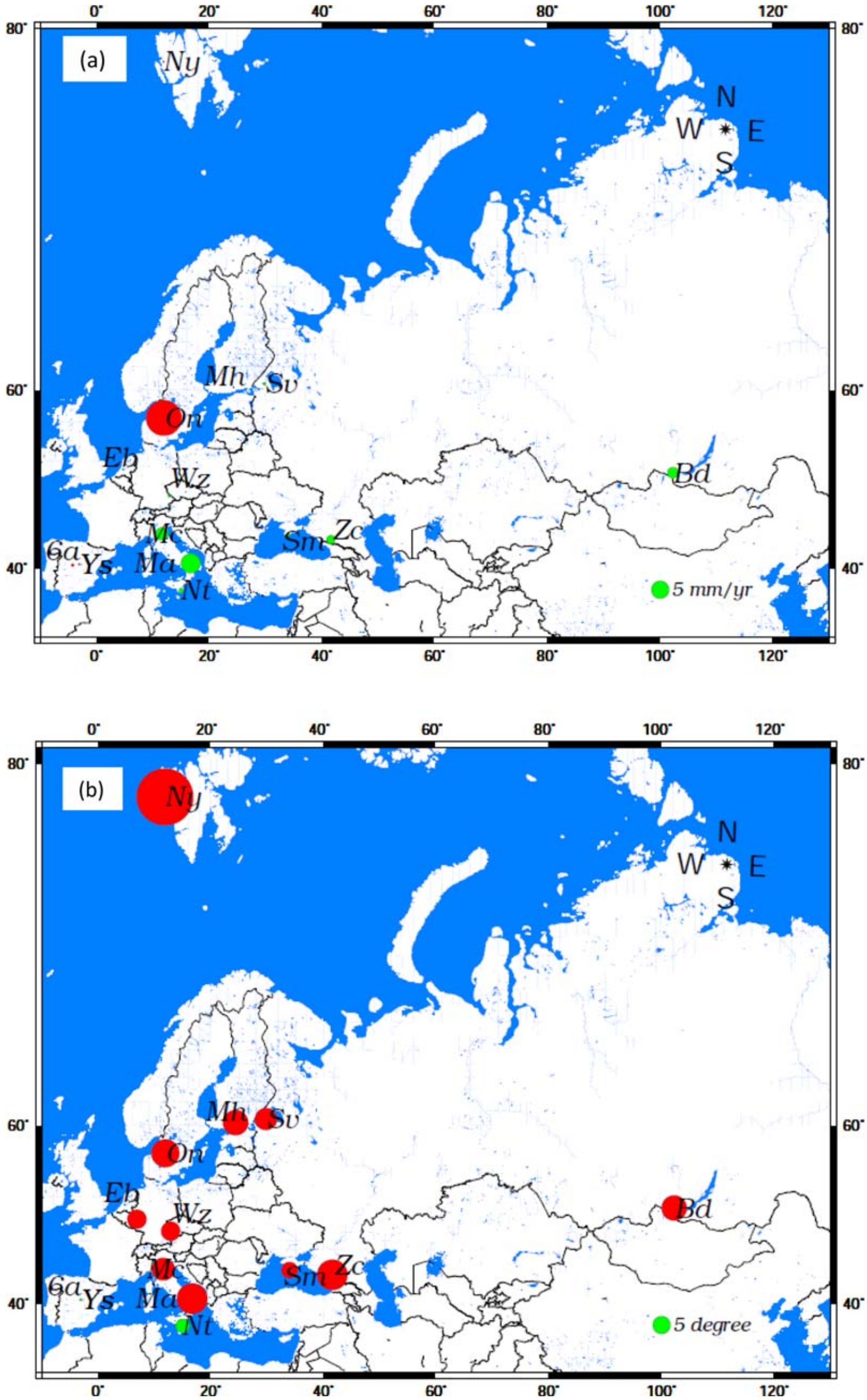


8 (a) The absolute differences of magnitude and (b) direction of the horizontal motion between VLBI estimated velocities and the modelled values from GSRM2.1. Green and red colours illustrate positive and negative differences, respectively

of Europe fit better to NUVEL1-A values, relative to other parts of this region. Comparison between the results presented in Figs. 11 and 12 show that there a larger discrepancy, in terms of magnitude and direction, between the SLR results and NUVEL1-A with respect to GSRM2.1 model.

5. Comparing the differences between SLR and VLBI results with respect to NUVEL-1A and GSRM2.1 model

The mean of the absolute value of differences of magnitude and direction of the current geodetic results with



9 (a) The absolute differences of magnitude and (b) direction of the VLBI estimated velocities with respect to NUVEL1-A. Green and red colours show positive and negative differences respectively

respect to the NUVEL1-A, and the GSRM2.1 values are provided in Table 5. The following points can be deduced from this table contents: (1) The comparison of SLR and VLBI results with the NUVEL1-A and GSRM2.1 model shows a larger azimuth discrepancy than corresponding magnitude inconsistency. (2) Between predicted values

Table 3 Comparison of the average differences between new VLBI results and Krásná *et al.* (2013) results with respect to the NUVEL1-A model in Europe

This paper	Results	Krásná *et al.* (2013)	Results
Azimuth −5.60 degree	Magnitude 1.14 mm/yr.	Azimuth −5.81 degree	Magnitude 1.51 mm/yr.

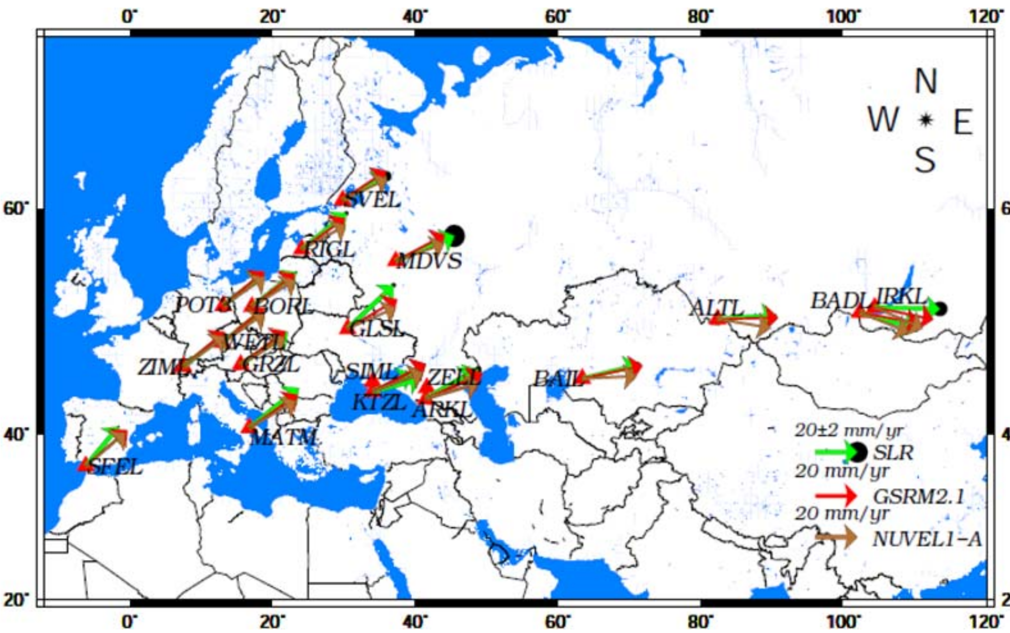
from GSRM2.1 and NUVEL1-A, GSRM2.1 values show greater agreement with the geodetic (VLBI and SLR) results. (3) GSRM2.1 is a geodetic-based model, while NUVEL1-A values are predicted based on geological evidence, regarding this statement and the second deduction, it seems that there are predicted tectonic motions which are not confirmed by observational evidence (geodetic techniques). (4) However, we recognise a better agreement between the VLBI results and GSRM2.1 values. (5) Both NUVEL1-A and GSRM2.1 values are closer to VLBI results relative to SLR technique. (6) In each comparison of SLR or VLBI with respect to NUVEL1-A and GSRM2.1 model, differences of the magnitude inconsistencies between two models are smaller than directions.

Totally, our results report that GSRM2.1 and NUVEL1-A can provide reliably predicted values in the tectonically stable areas such as the central part of Europe, because of the normal and predictable motion in this region. However, noticeable detected discrepancies in the highly active tectonic areas, including the northern part of the Black Sea (Tari *et al.* 2000) and

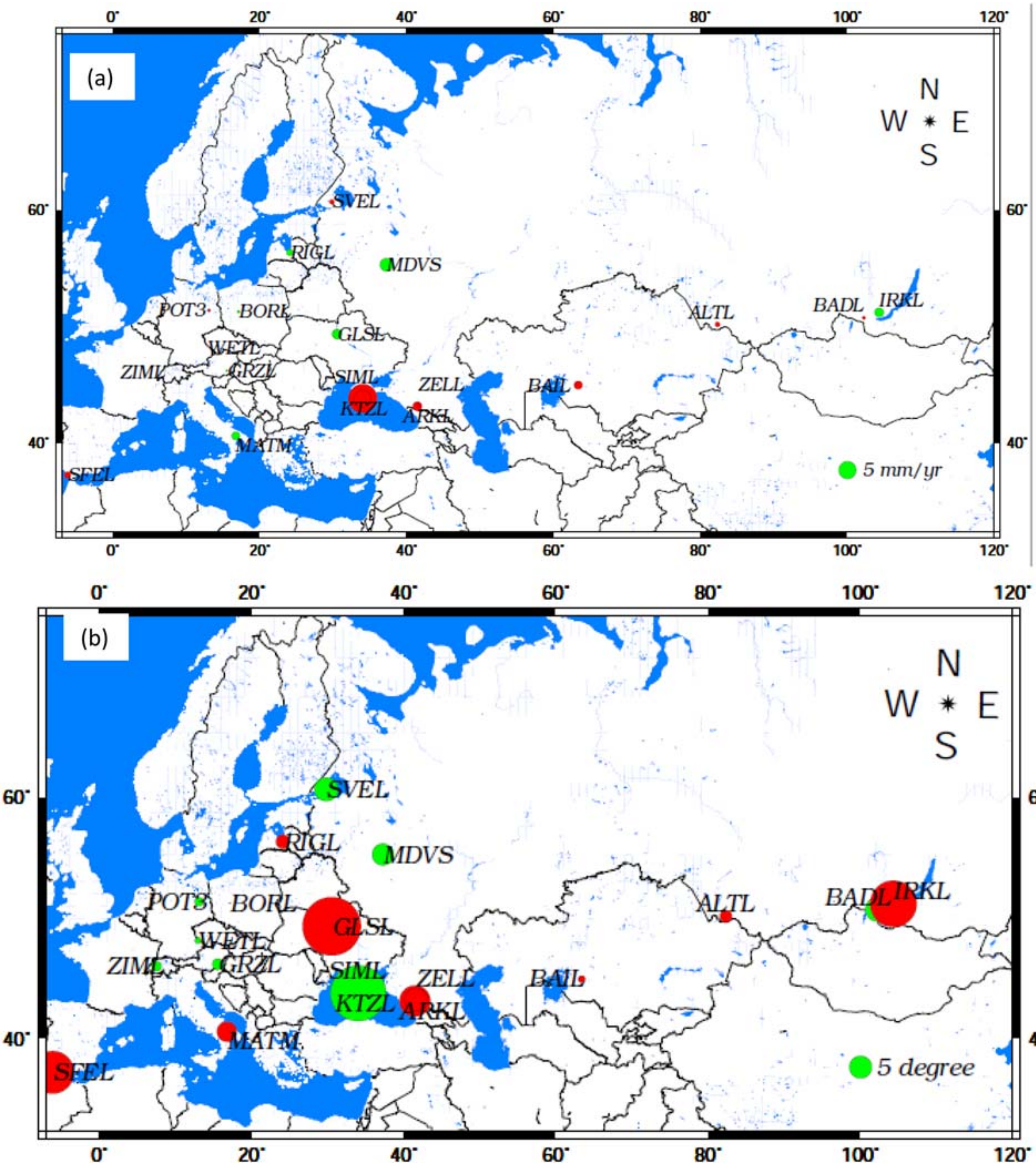
Table 4 Estimated velocities of SLR stations and their associated formal error

Station code	CPD PAD ID	V_e (mm/yr.)	V_n (mm/yr.)	V_u (mm/yr.)	Magnitude of horizontal motion
SIML	1873	20.793 ± 0.06	8.6867 ± 0.05	−3.04 ± 0.28	22.535
MDVS	1874	27.86 ± 2.02	12.01 ± 2.15	−6.96 ± 2.26	30.34
ALTL	1879	27.41 ± 0.22	1.92 ± 0.20	−4.88 ± 0.21	27.48
RIGL	1884	21.20 ± 0.40	17.12 ± 0.39	−5.04 ± 0.39	27.25
ARKL	1886	22.71 ± 0.60	13.46 ± 0.55	−0.24 ± 0.55	26.40
BAIL	1887	26.26 ± 0.67	6.39 ± 0.61	12.02 ± 0.61	27.03
SVEL	1888	20.81 ± 0.97	11.35 ± 0.98	−2.24 ± 0.86	23.71
ZELL	1889	24.50 ± 0.62	13.50 ± 0.59	−1.81 ± 0.59	27.97
BADL	1890	26.49 ± 0.60	−7.53 ± 0.56	2.81 ± 0.53	27.53
IRKL	1891	31.04 ± 1.46	−0.72 ± 1.39	−6.61 ± 1.35	31.05
KTZL	1893	22.88 ± 0.15	6.20 ± 0.13	3.34 ± 0.13	23.70
SFEL	7824	15.54 ± 0.21	18.67 ± 0.18	−0.33 ± 0.18	24.29
BORL	7811	21.01 ± 0.19	16.47 ± 0.18	1.64 ± 0.18	26.70
GLSL	1824	21.78 ± 0.44	20.61 ± 0.42	−15.41 ± 0.41	29.99
ZIML	7810	20.23 ± 0.04	15.80 ± 0.04	0.21 ± 0.04	25.67
GRZL	7839	22.55 ± 0.07	15.42 ± 0.06	−0.63 ± 0.07	27.32
POT3	7841	19.22 ± 0.07	14.97 ± 0.07	−0.60 ± 0.07	24.36
MATM	7941	23.53 ± 0.04	19.00 ± 0.04	−0.50 ± 0.04	30.24
WETL	8834	20.58 ± 0.07	15.70 ± 0.08	1.48 ± 0.08	25.88

Notes: V_e, V_n, V_u are indicators of east, north and up motion, respectively. All values are reported in mm/yr.



10 The velocity of SLR stations with their 95% confidence ellipse (green arrows). Red and brown arrows indicate GSRM2.1 and NUVEL-1A values, respectively



11 (a) The absolute differences of magnitude and (b) direction of the horizontal motion between SLR- deduced velocities and the modelled values from GSRM2.1. Green and red colours illustrate positive and negative differences, respectively

Mediterranean Sea (McKenzie 1972), can be interpreted as a result of the very complex tectonic motions in these regions.

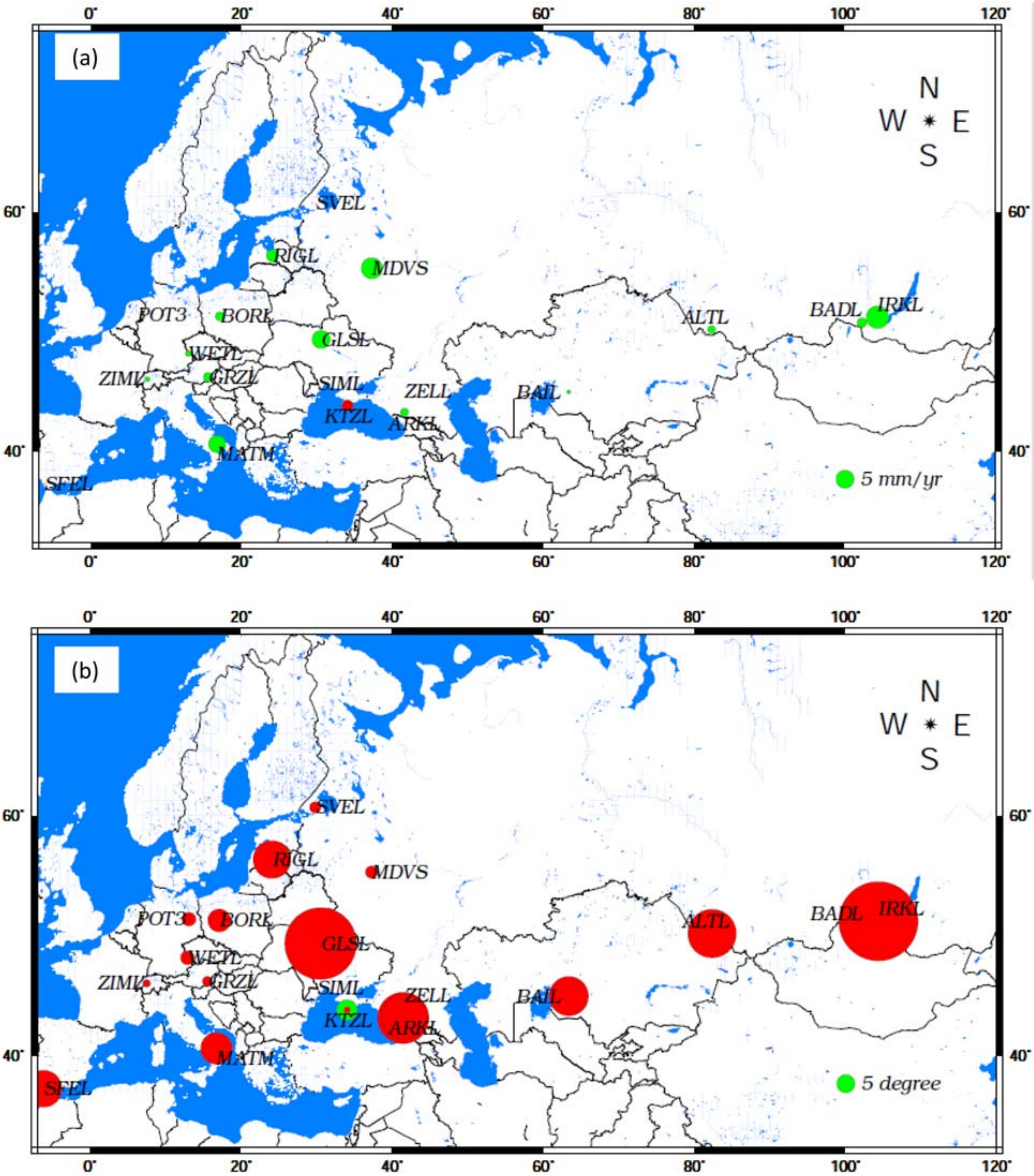
The last part is devoted to the investigation of difference of direction and magnitude of horizontal motion between geodetic results and values from the GSRM2.1 and NUVEL1-A model at VLBI stations co-located with SLR sites.

For co-located stations in SLR and VLBI networks, magnitude and direction discrepancies between geodetic and modelled values are listed in Table 6.

The magnitude and direction of estimated velocities at Matera (Ma) site are larger and smaller, respectively, than the corresponding predicted values. Directions and magnitude of geodetic horizontal motion at Zelenchk (Zc) are smaller than the corresponding predicted values from the GSRM2.1 model. However, magnitude and direction of the geodetic estimated velocities at this site are larger and smaller than modelled values from NUVEL1-A.

6. Conclusions

In this work, we demonstrated that there is a better agreement between geodetic results and values from a geodetic-based model (GSRM2.1 model) than from a geological-based model (NUVEL1-A model); it implies that there are predicted tectonic motions which are not



12 **(a) The absolute differences of magnitude and (b) direction of the horizontal motion between SLR-deduced velocities and the modelled values from NVUEL1-A. Green and red colours illustrate positive and negative differences, respectively**

confirmed by observational evidence (geodetic techniques). Moreover, the modelled values are in better agreement with VLBI results than with SLR results. Another point is that in the geodynamically stable regions, such as the central part of Europe, the modelled values and the geodetic results are more consistent.

Table 5 Mean of the absolute value of differences of magnitude and direction of the new geodetic results with respect to the NUVEL1-A and the GSRM2.1 predicted values

Technique	$\|\text{GSRM2.1}\|$ (mm/yr.)	$\|\text{NUVEL}-1\text{A}\|$ (mm/yr.)	$\|Az_{\text{GSRM2.1}}\|$ Degree)	$\|Az_{\text{NUVEL}-1\text{A}}\|$ Degree)
SLR	2.10	2.42	5.20	8.32
VLBI	1.41	1.58	2.21	6.29

Table 6 The difference of direction and magnitude of horizontal motion between geodetic results and modelled values at co-located sites in SLR and VLBI networks

	GSRM2.1-SLR		NUVEL1-A -SLR		GSRM2.1-VLBI		NUVEL1-A -VLBI	
STA	Magnitude (mm/yr.)	Azimuth (Deg.)	Magnitude (mm/yr.)	Azimuth (Deg.)	Magnitude (mm/yr.)	Azimuth (Deg.)	Magnitude (mm/yr.)	Azimuth (Deg.)
Sv	−1.32	5.26	0.22	−3.09	−0.54	2.19	1.00	−6.16
Wz	−0.09	1.29	1.50	−3.82	−0.73	−0.25	0.86	−5.36
Ma	2.31	−4.40	4.77	−8.72	3.03	−4.35	5.48	−8.66
Sm	−6.00	4.88	−3.10	−1.76	−1.66	2.11	1.24	−4.55
Zc	−1.01	−5.14	2.19	−12.48	−0.81	−1.25	2.39	−8.59
Bd	−1.06	5.43	2.61	−6.12	−0.59	4.45	3.08	−7.10

Comparing our geodetic results and modelled values from GSRM2.1 and NUVEL1-A at VLBI stations co-located with SLR sites, provide the following consequences: the magnitude and direction of estimated velocities at Matera (Ma) site are larger and smaller, respectively, than the corresponding predicted values. Directions and magnitude of geodetic horizontal motion at Zelenchk (Zc) are smaller than the corresponding predicted values from the GSRM2.1 model. However, magnitude and direction of the geodetic estimated velocities at this site are larger and smaller than modelled values from NUVEL1-A. Comparison between VLBI results and modelled values from NUVEL1-A and GSRM2.1 models suggests that post-glacial rebound effects in NYALES20 (Ny) caused the noticeable differences between the direction of modelled horizontal motion and the azimuth of geodetic motion. The present study reveals slightly smaller differences between VLBI and NUVEL1-A than found by Krásná *et al.* (2013).

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Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

We applied data and observations which had been acquired from the following mentioned addresses:

(1) SLR coordinates time-series were gathered from https://cddis.nasa.gov/archive/slr.

(2) VLBI observations were provided from https://ivscc.gsfc.nasa.gov/sessions/.

(3) In this paper, the modelled velocities were acquired from the UNAVCO Plate Motion Calculator, refer to the next link: https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html

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