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Investigation of crustal motion in Europe by analysing the European VLBI sessions

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Abstract Since 1990 the International VLBI Service for Geodesy and Astrometry (IVS) has been performing geodetic Very Long Baseline Interferometry (VLBI) observations within the European geodetic VLBI network. In this work, 114 European VLBI sessions from January 1990 to September 2011 are analysed using the Vienna VLBI Software (VieVS). A total of 58 baselines with lengths ranging from 59 m to 4581 km are investigated and the lengths of most of them indicate repeatabilities at the sub-centimetre level. The horizontal station motions which describe the motion of the Eurasian plate are compared to the NUVEL-1A and MORVEL tectonic plate models. Intraplate crustal motions are investigated by estimating the station velocities with respect to Wettzell (Germany), a station on the geodynamically stable part of Eurasia. The northern part of Europe is dominated by the postglacial isostatic rebound, confirmed by four VLBI sites in this region with an uplift from 2.89 ± 0.71 mm/yr (Svetloe, Russia) to 7.23 ± 1.00 mm/yr (Ny-Ålesund, Norway) with respect to the central part of the European plate. Besides the vertical uplift, these radio telescopes evidence a horizontal motion from the centre of the former ice sheet towards its border. In the southern part of Europe the motion of the VLBI sites is caused by the collision of the African plate with the Eurasian plate, while the stations on the stable part of Europe do not present any significant relative motions. Our results are compared against those by Haas et al. (J. Geodyn. 35:391–414, 2003) and with velocities of the current reference frame of the International Global Navigation Satellite Systems Service.

Keywords Crustal motion · Geodetic VLBI · Reference frame · Plate tectonics · European geodetic VLBI network

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1 Introduction

Since 1990 special geodetic Very Long Baseline Interferometry (VLBI) observing sessions using only European VLBI stations have been carried out. The purpose of these observations is the determination of crustal deformation and the realisation of a precise and reliable European reference frame as a basis for regional Global Navigation Satellite System (GNSS) networks that have been established in Europe for densification purposes (Haas et al. 2000).

In the past, there were many determinations of crustal motion derived from observations of the European geodetic VLBI network. One of the first investigations was done by Campbell et al. (1993) followed by Ward (1994). With more VLBI data available several new studies followed, e.g., by Campbell and Nothnagel (2000), Haas et al. (2000, 2002, 2003), Vennebusch (2003), or Sarti et al. (2010). All these groups analysed basically the same data but covering different time spans and using different software and approaches.

The motions within the European plate are also monitored by several dedicated Global Positioning System (GPS) projects. The uplift of Fennoscandia caused by the glacial isostatic rebound is mapped within the continuous GPS project BIFROST (Baseline Inferences for Fennoscandian Rebound Observations Sea Level and Tectonics) which was initiated in 1993 (e.g., Milne et al. 2001; Johansson et al. 2002; Scherneck et al. 2003; Bergstrand et al. 2007). One year later a Central European GPS Geodynamic Reference Network (CEGRN) was established to integrate the geodynamic research in central Europe covering 14 countries in the region (Fejes 2002). Several measurement campaigns were organised to determine tectonic motions and strain rates from the GPS data (Grenerczy et al. 2000, 2005; Caporali et al. 2009).

Malkin et al. (2001) compared baseline lengths and their rates determined from VLBI and GPS observations and one of the latest rigorous determinations of crustal motion derived from observations of the European geodetic VLBI network was done by Haas et al. (2003) who analysed 62 European sessions between January 1990 and December 2001. Since then, the geophysical and astronomical models (tropospheric mapping functions, atmospheric loading, precession-nutation) have been improved and a significantly larger time span of observations is now available. Therefore, a new determination of crustal motion in Europe by VLBI is necessary and of interest.

In this work all sessions between January 1990 and September 2011 (114 sessions) are analysed. In order to study the quality of the European geodetic VLBI data, the baseline length repeatabilities are determined in a first step (Sect. 4). Then, a global adjustment of all European sessions (a so-called global solution) is carried out to estimate a terrestrial reference frame (TRF), i.e., station coordinates and velocities. The station velocities are transformed to local (north, east, height) coordinate systems and the absolute values (Sect. 5.1) as well as relative values with respect to station Wettzell (Sect. 5.2) are investigated. The new crustal deformation results are compared to theoretical crustal motion predicted by the NUVEL-1A (DeMets et al. 1994) and the MORVEL (DeMets et al. 2010) plate tectonic models. Furthermore, our VLBI estimates are compared to those obtained by Haas et al. (2003) in Sect. 5.2.1, and also to GNSS results (Rebischung et al. 2012) (Sect. 5.2.2).

2 The European geodetic VLBI network

In 1990 European geodetic VLBI groups decided to carry out VLBI observations within the European network in regular intervals. The purpose of the European geodetic VLBI observations is the determination of intraplate crustal deformations and the realisation of a

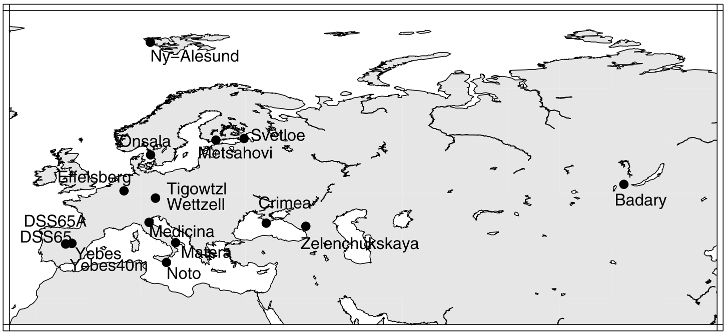

Fig. 1 The European geodetic VLBI network

Table 1 The European geodetic VLBI sites, their operation history and ellipsoidal coordinates

Site	IVS Code	Operational	Latitude (ϕ, deg)	Longitude (λ, deg)
Badary	Bd	2007–now	51.77	102.23
Crimea	Sm	1994–now	44.40	33.98
Madrid (DSS65)	65	1987–2005	40.43	355.75
Madrid (DSS65A)	6a	2005–now	40.43	355.75
Effelsberg	Eb	1991–now	50.52	6.88
Karlsburg	Kr	1992	53.98	13.61
Matera	Ma	1990–now	40.65	16.70
Medicina	Mc	1983–now	44.52	11.65
Metsähovi	Mh	2005–now	60.22	24.39
Noto	Nt	1988–now	36.88	14.99
Ny-Ålesund	Ny	1994–now	78.93	11.87
Onsala	On	1976–now	57.40	11.93
Svetloe	Sv	2003–now	60.53	29.78
Tigowtzl	Tg	1997–2000	49.14	12.88
Toulouse	To	1992	43.56	1.48
Wettzell	Wz	1983–now	49.15	12.88
Yebes	Yb	1995–2004	40.52	356.91
Yebes40m	Ys	2009–now	40.52	356.91
Zelenchukskaya	Zc	2006–now	43.79	41.57

precise and reliable European reference frame as a basis for other space geodetic techniques (Haas et al. 2000; Campbell and Nothnagel 2010). Six European VLBI sites (Madrid, Matera, Medicina, Noto, Wettzell, Onsala) were part of the European geodetic VLBI network and four sessions were scheduled in this first year beginning with the session designated as EUROPE-1 on January 26, 1990. During the following 20 years the European geodetic VLBI network has been extended significantly when new radio telescopes were built and became part of the network. Figure 1 depicts all European VLBI sites with observational history longer than two years. Table 1 lists the observation history of the European VLBI radio telescopes together with their coordinates, and Fig. 2 gives an overview about the number of European sessions in which the VLBI sites were participating. We restrict our in-

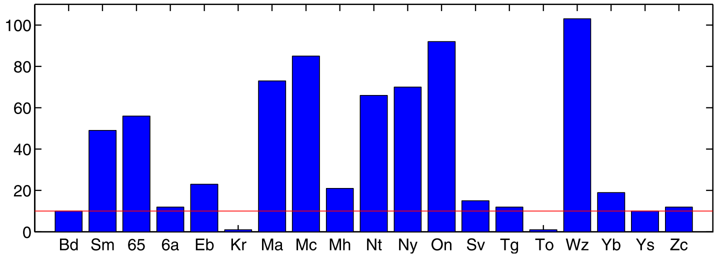

Fig. 2 Number of European VLBI sessions per station. The *horizontal line* indicates the threshold of ten sessions. Stations Toulouse (To) and Karlsburg (Kr) are not considered in this work since their participation does not reach this limit

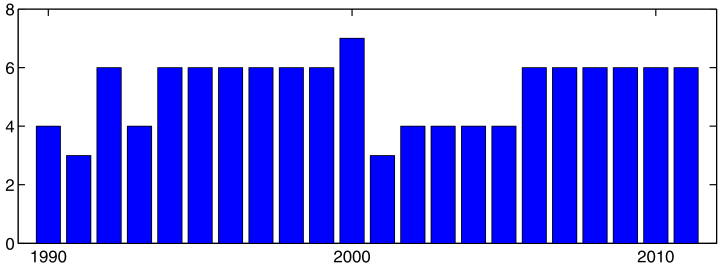

Fig. 3 Number of European VLBI sessions per year (the last session in 2011 is not included in this work)

vestigations on those VLBI sites which participated in ten or more sessions, which implies an observation period of at least two years.

The observing program for the European geodetic VLBI sessions is organised by the Institute of Geodesy and Geoinformation of the University of Bonn and is incorporated into the master files of the International VLBI Service for Geodesy and Astrometry (IVS). The sessions are correlated at the Max Planck Institute for Radio Astronomy in Bonn and the databases are freely available for further analysis via the web site of the IVS.[1] Currently, approximately six sessions per year are observed (Fig. 3). The duration of the sessions is 24 h and the number of observed sources per session has increased during the time from about 25 sources in the early 1990s to approximately 45 sources in the year 2010. In this work 114 sessions have been analysed up to the session designated as EUROPE-113 (September 5, 2011). Please note that although the numbering of the sessions is continuous, there was an additional session EUROPE-M in 1990, which increases the total number of sessions by one.

3 Data analysis

The European geodetic VLBI sessions from the last nearly 22 years (January 1990 to September 2011) are analysed using the Vienna VLBI Software (VieVS; Böhm et al. 2012). VieVS has been developed since 2008 at the research group Advanced Geodesy at the

[1] http://ivscc.gsfc.nasa.gov/products-data/data.html (May 2013).

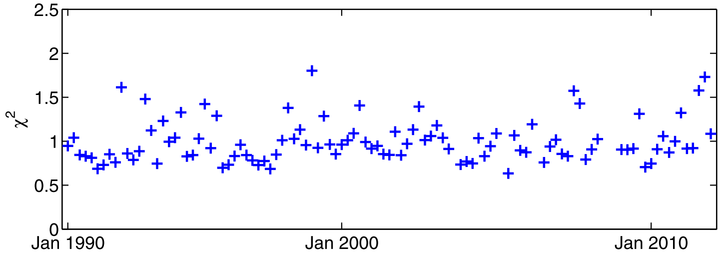

Fig. 4 A posteriori variance factor of the European VLBI sessions

Department of Geodesy and Geoinfomation of the Vienna University of Technology. The models used in VieVS are in accordance with the International Earth Rotation and Reference Systems Service (IERS) Conventions 2010 (Petit and Luzum 2010). More information about the VLBI data analysis can be found e.g. in Sovers et al. (1998) or Schuh and Böhm (2013). The European VLBI sessions are processed with the default options of VieVS, which means that station coordinates are estimated using the no-net-translation (NNT) and the no-net-rotation (NNR) condition on VTRF2008 (VLBI Terrestrial Reference Frame 2008, Böckmann et al. 2010). Atmospheric loading (Petrov and Boy 2004) and tidal ocean loading (Scherneck 1991) based on the ocean model FES2004 (Lyard et al. 2006) are considered and the influence of thermal deformation of the radio telescopes is taken into account according to Nothnagel (2009). The radio source coordinates are fixed to ICRF2 (Fey et al. 2009) and five constant Earth orientation parameters (x-pole, y-pole, dUT1, dX, and dY) are estimated once per session with respect to the IERS EOP 08 C04 series (Gambis 2004; Bizouard and Gambis 2009) that is used as a priori.

For the data analysis only those observations are used which are labelled as highest data quality by the VLBI correlator. No cut-off elevation angle is applied and with a simple outlier test bad observations are detected and excluded from the processing. Relative clock parameters with respect to a reference clock in each session are estimated every 60 minutes in addition to a quadratic clock polynomial. Atmospheric zenith wet delays are estimated as piece-wise linear offsets in 30 minutes intervals using the Vienna Mapping Functions VMF1 (Böhm et al. 2006). Horizontal gradients in east and north direction are estimated every six hours to consider horizontal asymmetries in the atmospheric refractivity profile.

All investigated European VLBI sessions prove to be of good quality, although in 36 sessions some additional issues have to be taken into account compared to a usual analysis praxis (e.g. clock breaks). After the analysis, the a posteriori variance factor of unit weight (χ^2, Eq. (1)) in almost all experiments is below 1.5 (Fig. 4).

$$\chi^2 = \frac{v^T P v}{n - u}, \tag{1}$$

where v contains the post-fit residuals, P denotes the weight matrix consisting of squared reciprocal values of the a priori uncertainty of the observations increased quadratically by 1 cm, n gives the number of observations and u the number of unknown parameters.

4 Baseline length repeatability

Baseline length repeatabilities are representative measures of the quality of VLBI observations because baselines are invariant to rotations. In this analysis the repeatability is de-

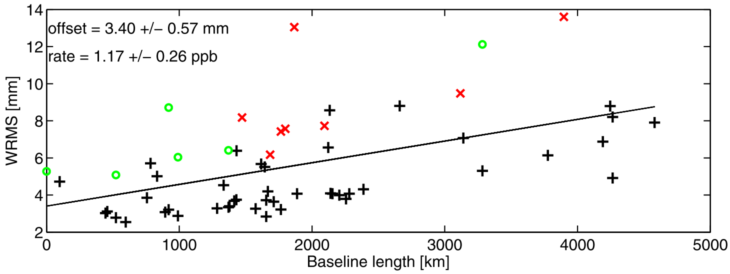

Fig. 5 Baseline length repeatabilities for the European VLBI sessions. *Red crosses* indicate baselines with station Crimea, *green circles* baselines with station Tigowtzl. The regression line includes all 58 baselines (Color figure online)

fined as the weighted root mean square (WRMS) deviation of the estimated baseline lengths where we use the formal errors of the baseline lengths estimated in single session adjustments as weights. Since the time series are based on observations carried out over more than 20 years, linear trends that represent the variations are subtracted before calculating the WRMS values. In Fig. 5 the baseline length repeatabilities in millimetres are plotted against baseline lengths in kilometres. In total 127 baselines were observed in the European geodetic VLBI sessions in the investigated time frame. Baseline length repeatabilities are estimated for only 58 of the 127 baselines, since only these baselines were observed ten or more times. The baselines lengths ranging from 59 m (Wettzell-Tigowtzl) to 4581 km (Ny-Ålesund-Noto). Due to the moderate distances in Europe most of the baselines show good repeatabilities hardly exceeding 10 mm. Slightly worse results are obtained for baselines including the station Crimea (plotted as red crosses) and the station Tigowtzl (shown as green circles). At station Crimea several technical problems have been reported since this VLBI site was put into operation (Nesterov and Volvach 1999). At the baselines including station Tigowtzl the larger WRMS may be caused by the fact that Tigo is a small 6-metres transportable telescope which is providing a lower signal-to-noise ratio and thus less precise VLBI recordings.

We estimated a regression line between the baseline length and the WRMS including all considered 58 baselines. It is described by an offset of 3.40 ± 0.57 mm and an offset rate of 1.17 ± 0.26 ppb.

5 Velocities estimated in a global solution

The main part of our analysis is the estimation of station coordinates and velocities within a global solution. It is done by using the Vie_GLOB module (Krásná et al. 2013) of VieVS, which has the capability to estimate parameters that are common to all VLBI sessions. This analysis yields a new TRF, realised with the estimated coordinates and linear velocities of the European stations. For a reliable estimation of station velocities, sufficiently long time series of measurements have to be available. Therefore, we only considered stations that participated in ten or more sessions for the global adjustment (stations Karlsburg and Toulouse do not reach this limit). Furthermore, at stations that are located in the vicinity of each other, like the old and the new antenna in Madrid (DSS65 and DSS65A) or the two antennas in Wettzell (Tigowtzl and Wettzell), relative constraints for the velocity are applied, forcing the estimated velocity to be identical. In case of the two antennas in Yebes

Table 2 Components of absolute station velocities and their corresponding formal errors estimated by analysing European VLBI sessions compared to the NUVEL-1A and the MORVEL plate tectonic models, which predict horizontal motion only. All values are given in mm/yr. dN is the velocity in north direction, dE in east direction, and dH is the height component

IVS Code	This work			NUVEL-1A		MORVEL	
	dN	dE	dH	dN	dE	dN	dE
Bd	-10.75 ± 1.93	$+34.15 \pm 2.87$	-13.43 ± 6.58	-9.33	$+23.11$	-7.83	$+22.76$
Sm	$+13.24 \pm 0.17$	$+25.34 \pm 0.17$	-0.09 ± 1.02	$+9.16$	$+23.95$	$+10.36$	$+22.12$
65	$+17.50 \pm 0.25$	$+18.35 \pm 0.21$	$+4.29 \pm 1.27$	$+15.68$	$+18.62$	$+15.92$	$+16.46$
6a	$+17.50 \pm 0.25$	$+18.35 \pm 0.21$	$+4.29 \pm 1.27$	$+15.68$	$+18.62$	$+15.92$	$+16.46$
Eb	$+16.44 \pm 0.12$	$+17.79 \pm 0.12$	-0.58 ± 0.58	$+14.39$	$+18.99$	$+14.94$	$+16.87$
Ma	$+19.18 \pm 0.09$	$+23.64 \pm 0.11$	$+0.22 \pm 0.22$	$+12.81$	$+22.01$	$+13.63$	$+19.97$
Mc	$+18.02 \pm 0.08$	$+22.21 \pm 0.10$	-2.78 ± 0.32	$+13.68$	$+20.79$	$+14.36$	$+18.70$
Mh	$+13.70 \pm 0.29$	$+20.28 \pm 0.27$	$+3.11 \pm 1.27$	$+11.30$	$+20.39$	$+12.30$	$+18.53$
Nt	$+19.89 \pm 0.08$	$+21.53 \pm 0.14$	-0.52 ± 0.06	$+13.12$	$+22.07$	$+13.89$	$+20.04$
Ny	$+14.98 \pm 0.28$	$+9.25 \pm 0.56$	$+6.85 \pm 0.72$	$+13.62$	$+12.94$	$+14.31$	$+11.18$
On	$+15.00 \pm 0.10$	$+16.87 \pm 0.01$	$+2.75 \pm 0.41$	$+13.62$	$+18.64$	$+14.31$	$+16.60$
Sv	$+12.63 \pm 0.12$	$+19.99 \pm 0.14$	$+2.51 \pm 0.43$	$+10.12$	$+21.20$	$+11.25$	$+19.43$
Tg	$+15.57 \pm 0.08$	$+20.09 \pm 0.08$	-0.38 ± 0.28	$+13.47$	$+20.33$	$+14.19$	$+18.26$
Wz	$+15.57 \pm 0.08$	$+20.09 \pm 0.08$	-0.38 ± 0.28	$+13.47$	$+20.33$	$+14.19$	$+18.26$
Yb	$+16.36 \pm 0.23$	$+18.24 \pm 0.20$	-0.36 ± 0.33	$+15.57$	$+18.81$	$+15.85$	$+16.66$
Ys	$+15.37 \pm 0.96$	$+22.72 \pm 0.92$	$+17.72 \pm 3.56$	$+15.57$	$+18.81$	$+15.85$	$+16.66$
Zc	$+8.82 \pm 0.87$	$+27.63 \pm 0.79$	-17.59 ± 3.99	$+7.27$	$+24.74$	$+8.61$	$+23.03$

this procedure cannot be used because the position of the new antenna Yebes40m is not contained in the a priori VTRF2008 catalogue and therefore the initial information about the velocity of these two stations is different. The constraining of velocities is also used when a discontinuity in the station position is caused by a rail repair of the antenna. In such a case we estimate two different sets of coordinates in the global adjustment but we force the velocities before and after the positions' change to be equal. The affected stations are Medicina (repair of azimuth rail, July 1, 1996), Effelsberg (repair of azimuth rail, October 1, 1996), DSS65 at Madrid (repair of azimuth rail, April 15, 1997), and Zelenchukskaya (rail replacement, July 1, 2007). The estimated station velocities (transformed into local topocentric (north, east, height) reference frames) are summarized in the columns two to four of Table 2, and the horizontal motions are plotted in Fig. 6 in black colour.

5.1 Absolute station velocities

Absolute station velocities are estimated for 17 European VLBI sites. The formal errors of the estimated station velocities listed in Table 2 reveal that the uncertainties of the vertical motions are two to five times larger than those of the respective horizontal motion. This is a usual phenomenon in space geodetic techniques where we find a strong propagation of troposphere delay errors into the height component and a degradation of the precision of the height estimates. Table 2 indicates that Badary (Bd) has a formal error larger than 1 mm/yr in all three components and therefore we exclude it from any further analysis. Station Crimea (Sm), the two stations in Madrid (65 and 6a), Metsähovi (Mh), the new 40-m antenna in Yebes (Ys) and Zelenchukskaya (Zc) have formal errors larger than 1 mm/yr for the height

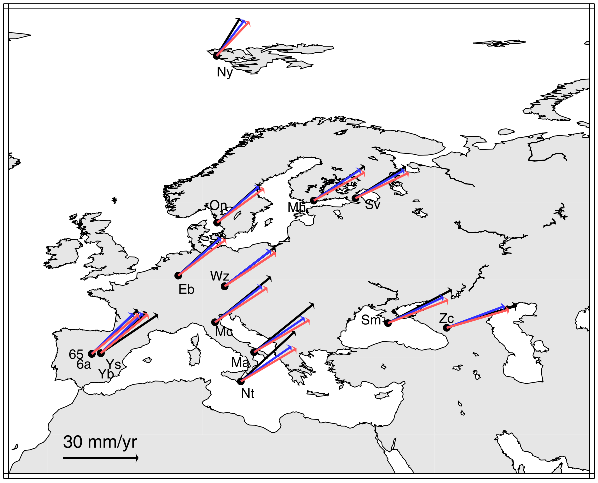

Fig. 6 Absolute horizontal station velocities derived from European VLBI sessions (*black colour*) compared to station velocities from the NUVEL-1A (*light red colour*) and MORVEL (*dark blue colour*) plate tectonic model (Color figure online)

component. The reason for the larger formal error of the velocity components at the 40-m telescope in Yebes is the short (since 2009) observation period making the estimation of a reliable station velocity impossible. Velocities of the other stations have formal errors of less than 1 mm/yr in both directions, horizontal and vertical. The absolute station velocities demonstrate the known motion of the Eurasian plate in northeast direction with a velocity of up to 30 mm/yr in the International Terrestrial Reference Frame (ITRF).

In the following the absolute station velocities obtained in this work are compared to two plate tectonic models, NUVEL-1A (DeMets et al. 1994) and MORVEL (DeMets et al. 2010). NUVEL-1A is a global model of horizontal plate velocities which originates from NUVEL-1 (DeMets et al. 1990). The theoretical computation of the motion of 12 tectonic plates is based on geodynamic data such as seafloor spreading rates, azimuths of oceanic transform faults and earthquake slip vectors at the plate boundaries. The transformation from NUVEL-1 to the NUVEL-1A model is done by a slight recalibration of geomagnetic reversal time scales which is supposed to be about 3 million years (DeMets et al. 1990). MORVEL by DeMets et al. (2010) is a more recent global model for the geological motion of 25 tectonic plates. It is based on many new data, revised seafloor spreading rates and updated plate geometries. For the estimation of the motions of six smaller plates GPS measurements were used (DeMets et al. 2010). For our study we obtain the linear horizontal station velocities in the European tectonic plate from the UNAVCO Plate Motion Calculator.[2] The components of the predicted horizontal velocities by the models NUVEL-1A and MORVEL are summarized in columns five to eight of Table 2 and plotted together with our estimates in Fig. 6. The differences of the estimated horizontal speed and its direction of our work with respect to the model predictions of the two theoretical models are given in Table 3 where the formal errors show the uncertainty of our estimation. It is evident that at almost all stations the magnitude of the estimated velocity from VLBI is larger than those predicted by the models. A better agreement in terms of the magnitude of the velocity is reached with the older NUVEL-1A model with an averaged difference of 1.51 ± 0.28 mm/yr (i.e., VLBI estimates are larger by 6.3 ± 1.2 %), whereas a comparison with the newer MORVEL model shows an averaged difference of 2.73 ± 0.28 mm/yr (11.9 ± 1.2 %) (computed without Badary and Yebes40m

[2] http://www.unavco.org/community_science/science-support/crustal_motion/dxdt/model.html (May 2013).

Table 3 Differences of magnitude and direction of the horizontal velocity between our estimates and the predicted values from the NUVEL-1A and the MORVEL models. The magnitude is given in mm/yr and azimuth in degrees

IVS code	This work minus NUVEL-1A		This work minus MORVEL	
	Δ horiz. speed	Δ azimuth	Δ horiz. speed	Δ azimuth
Bd	$+10.88 \pm 2.16$	-4.51 ± 4.33	$+11.73 \pm 2.16$	-1.51 ± 4.33
Sm	$+2.95 \pm 0.23$	-6.66 ± 0.46	$+4.16 \pm 0.23$	-2.49 ± 0.46
65	$+1.01 \pm 0.32$	-3.54 ± 0.74	$+2.46 \pm 0.32$	$+0.40 \pm 0.74$
6a	$+1.01 \pm 0.32$	-3.54 ± 0.74	$+2.46 \pm 0.32$	$+0.40 \pm 0.74$
Eb	$+0.40 \pm 0.17$	-5.59 ± 0.40	$+1.69 \pm 0.17$	-1.21 ± 0.40
Ma	$+4.98 \pm 0.14$	-8.85 ± 0.26	$+6.26 \pm 0.14$	-4.74 ± 0.26
Mc	$+3.71 \pm 0.13$	-5.71 ± 0.25	$+5.02 \pm 0.13$	-1.53 ± 0.25
Mh	$+1.16 \pm 0.39$	-5.05 ± 0.92	$+2.23 \pm 0.39$	-0.46 ± 0.92
Nt	$+3.64 \pm 0.16$	-12.00 ± 0.30	$+4.93 \pm 0.16$	-8.01 ± 0.30
Ny	-1.18 ± 0.53	-11.84 ± 2.03	-0.55 ± 0.53	-6.30 ± 2.03
On	-0.51 ± 0.07	-5.49 ± 0.21	$+0.66 \pm 0.07$	-0.88 ± 0.21
Sv	$+0.15 \pm 0.18$	-6.77 ± 0.43	$+1.19 \pm 0.18$	-2.21 ± 0.43
Tg	$+1.03 \pm 0.11$	-4.25 ± 0.25	$+2.29 \pm 0.11$	$+0.07 \pm 0.25$
Wz	$+1.03 \pm 0.11$	-4.25 ± 0.25	$+2.29 \pm 0.11$	$+0.07 \pm 0.25$
Yb	$+0.08 \pm 0.30$	-2.27 ± 0.71	$+1.51 \pm 0.30$	$+1.68 \pm 0.71$
Ys	$+3.01 \pm 1.30$	$+5.54 \pm 2.74$	$+4.44 \pm 1.30$	$+9.49 \pm 2.74$
Zc	$+3.22 \pm 1.02$	-1.33 ± 2.11	$+4.42 \pm 1.02$	$+2.79 \pm 2.11$

because of the afore-mentioned reasons). Concerning the direction of the horizontal motion a systematic rotation of the European plate from our solution with respect to the NUVEL-1A model is visible with an average angle of -5.81 ± 0.67 deg. Comparing our estimates to MORVEL this rotation is reduced considerably to about -1.49 ± 0.67 deg. These results reveal that the magnitude of the velocity of the European plate motion provided by the older NUVEL-1A model is closer to the present-day geodetic measurements but a more realistic direction of station motions is obtained from the newer MORVEL model.

5.2 Station velocities with respect to Wettzell

In order to study the crustal motion within the European continent station velocities are expressed with respect to the station Wettzell. Wettzell is chosen as the reference station because it lies on the geodynamically stable part of Europe and the station shows good long-term stability in global VLBI solutions (Ma and Ryan 1998). We subtracted the station velocity of Wettzell from the velocity of each VLBI site given in the local (north, east, height) frames. This implies that we can fully discriminate between the horizontal motion on the Eurasian plate and the changes in the height which are e.g. caused by the glacial isostatic adjustment. The station velocities with respect to Wettzell and their formal errors are listed in Table 4 and plotted in Fig. 7 (horizontal motions) and Fig. 8 (vertical motion). Haas et al. (2003) divided the area covered by the European geodetic VLBI network in three geodynamically meaningful parts, the northern, the central, and the southern part. Stations belonging to each of these parts present similar motions. The northern part (Ny-Ålesund (Ny), Onsala (On), Metsähovi (Mh), Svetloe (Sv)) is dominated by the postglacial isostatic rebound (Haas et al. 2000). Since the ice shield of the last ice age vanished (about 10000 years ago)

Table 4 Station velocities with respect to Wettzell and their corresponding formal errors from our analysis given in mm/yr

IVS code	This work		
	dN	dE	dH
Sm	−2.33 ± 0.25	+5.26 ± 0.25	+0.29 ± 1.30
65	+1.93 ± 0.33	−1.73 ± 0.29	+4.67 ± 1.55
6a	+1.93 ± 0.33	−1.73 ± 0.29	+4.67 ± 1.55
Eb	+0.87 ± 0.20	−2.29 ± 0.20	−0.21 ± 0.86
Ma	+3.61 ± 0.17	+3.55 ± 0.19	+0.60 ± 0.50
Mc	+2.45 ± 0.16	+2.12 ± 0.18	−2.40 ± 0.60
Mh	−1.87 ± 0.37	+0.20 ± 0.35	+3.48 ± 1.55
Nt	+4.32 ± 0.16	+1.44 ± 0.22	−0.14 ± 0.34
Ny	−0.59 ± 0.36	−10.83 ± 0.64	+7.23 ± 1.00
On	−0.57 ± 0.18	−3.22 ± 0.17	+3.13 ± 0.69
Sv	−2.94 ± 0.20	−0.10 ± 0.22	+2.89 ± 0.71
Yb	+0.78 ± 0.31	−1.85 ± 0.28	+0.02 ± 0.61
Ys	−0.20 ± 1.04	+2.64 ± 1.00	+18.10 ± 3.84
Zc	−6.75 ± 0.95	+7.55 ± 0.87	−17.21 ± 4.27

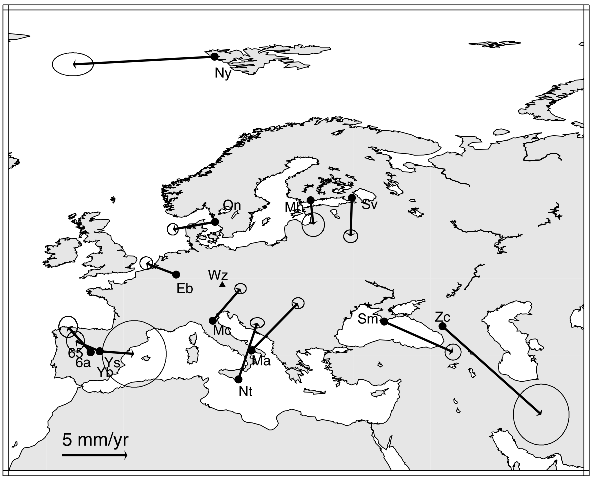

Fig. 7 Horizontal motions with respect to Wettzell. The *ellipses* display the 95 % confidence interval

the area has permanently uplifted. All four VLBI sites in this area show an uplift of at least 2.89 ± 0.71 mm/yr (Svetloe) with respect to Wettzell, and in particular Ny-Ålesund presents a very high uplift rate with 7.23 ± 1.00 mm/yr. Besides the vertical uplift the stations show a horizontal motion away from the centre of the former ice sheet located at the Arctic Circle (Lambeck et al. 1998) towards its border. Ny-Ålesund and Onsala are moving to the west, Metsähovi and Svetloe towards south. The central part of Europe (containing stations Wettzell (Wz) and Effelsberg (Eb)) is assumed to be stable. However, Effelsberg shows a horizontal motion with the dominant component of 2.29 ± 0.20 mm/yr towards west. Its estimated vertical motion is within the formal error. The southern part includes the area around the Mediterranean Sea (Madrid (65 and 6a), Yebes (Yb and Ys), Medicina (Mc), Matera (Ma), Noto (Nt)) and at the Black Sea (Zelenchukskaya (Zc) and Crimea (Sm)). The Spanish antennas in Madrid and the older telescope in Yebes are moving to northwest

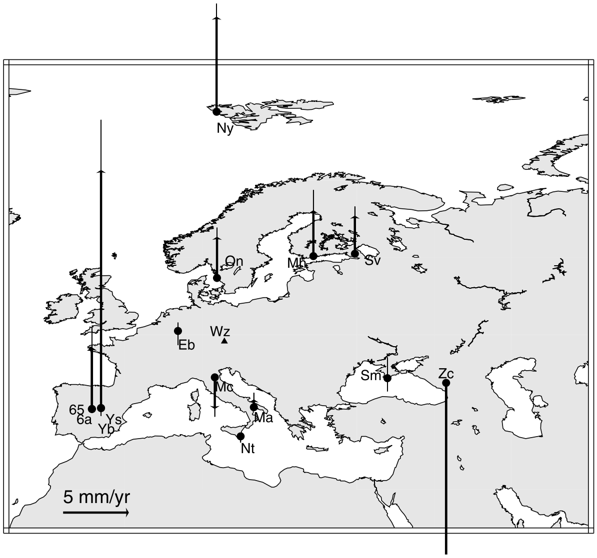

Fig. 8 Vertical motion with respect to Wettzell. The *bars* represent the formal errors

with velocities of 2.59 ± 0.44 mm/yr and 2.01 ± 0.38 mm/yr, respectively. The motion of the Italian VLBI sites is influenced by the collision of the African plate with the Eurasian plate, because the African plate is moving northwards pushing the Adriatic microplate in the same direction. The radio telescope in Noto (Sicily) demonstrates this effect very clearly: the station is moving by 4.32 ± 0.16 mm/yr towards north and 1.44 ± 0.22 mm/yr to the east. Matera and Medicina show similar motion but the eastward and northward components are almost equal. The subsidence of Medicina can be explained by extraction of ground water and gas in the Po valley (Tomasi et al. 1997). Matera and Noto do not show any significant vertical motion. The Black Sea stations (Crimea and Zelenchukskaya) are moving consistently towards southeast; however, in the vertical direction they provide different results: Crimea seems to be stable with respect to Wettzell while at Zelenchukskaya a subsidence of 17.21 ± 4.27 mm/yr occurs and no clear explanation can be provided for the large value and its formal error. Possibly, bad meteorological data used for tropospheric delay modelling at the station contribute to this effect.

We compare the crustal motion to results obtained by analysis of other space geodetic data. The relative station velocities with respect to Wettzell are compared to the analysis by Haas et al. (2003) in Sect. 5.2.1, and Sect. 5.2.2 shows the relation to the current reference frame of the International GNSS Service (IGS) IGS08 (Rebischung et al. 2012).

5.2.1 Study by Haas et al. (2003)

The station velocities with respect to Wettzell from our analysis are compared to the results of Haas et al. (2003) (Figs. 9 and 10, columns two till four of Table 5). In the southern part of Europe at stations Noto, Matera and Medicina a similar motion in the horizontal plane can be observed, where the direction and numerical values of the velocities together with their formal errors reach similar values in both analyses. At the remaining common stations the horizontal motions estimated in our analysis are larger than those presented by Haas et al. (2003). The largest discrepancy is found at station Ny-Ålesund, where our estimated motion of 10.83±0.64 mm/yr towards west is six times larger than that from the analysis by Haas

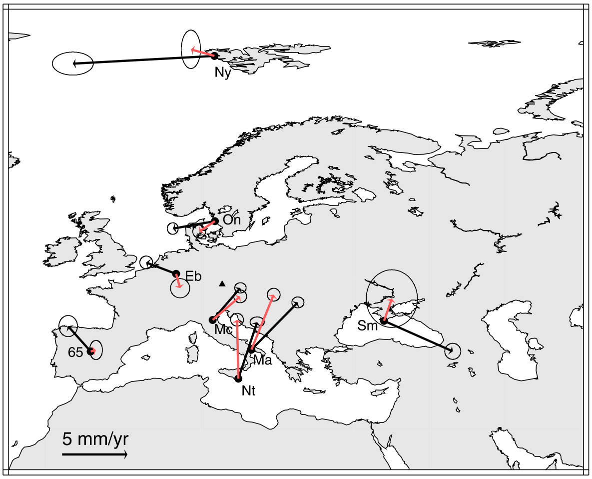

Fig. 9 Horizontal station velocities with respect to Wettzell from European VLBI sessions (in *black*) compared to Haas et al. (2003) (in *light red*). The *ellipses* display the 95 % confidence interval (Color figure online)

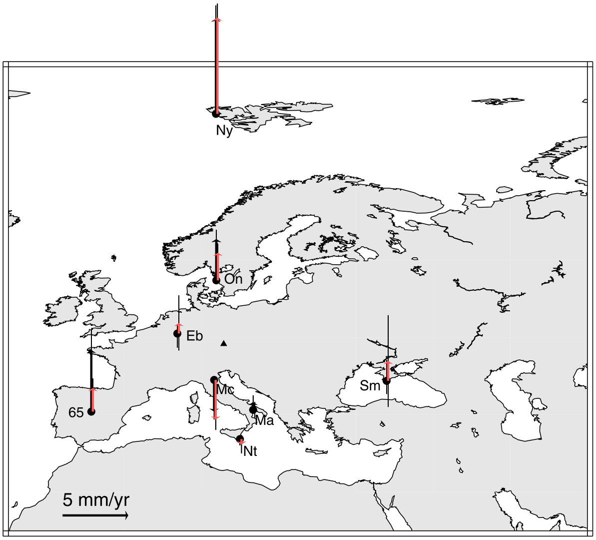

Fig. 10 Vertical station velocities with respect to Wettzell from European VLBI sessions (in *black*) compared to Haas et al. (2003) (in *light red*). The *bars* represent the formal errors (Color figure online)

et al. (2003) (1.8 ± 0.3 mm/yr). Another example is the horizontal motion at station Crimea where the velocity estimated by Haas et al. (2003) (1.8 ± 1.1 mm/yr) is in disagreement with our estimate of 5.75 ± 0.33 mm/yr towards southeast. The vertical motion of Crimea lies within its formal error in both analyses. Also at all other stations, except of the stations in Madrid, the estimated changes in the height agree with each other within their formal errors. Our estimated uplift of stations DSS65 and DSS65A (4.67 ± 1.55 mm/yr) is nearly three times larger than that reported by Haas et al. (2003) (1.8 ± 0.7 mm/yr); nevertheless, the reason for the relatively large formal error is unknown and should be further investigated.

5.2.2 GNSS data

Similar to VLBI measurements also GNSS data can be used for obtaining information about the motion of the Eurasian plate. The high spatial density of the receivers and continual ob-

Table 5 Station velocities with respect to Wettzell and their corresponding formal errors obtained by Haas et al. (2003) and from GNSS measurements (Rebischung et al. 2012). All values are in mm/yr

IVS code	Haas et al. (2003)			IGS code	GNSS		
	dN	dE	dH		dN	dE	dH
Sm	$+1.7 \pm 0.9$	$+0.6 \pm 0.8$	$+1.5 \pm 3.5$	CRAO	-3.6 ± 0.1	$+3.5 \pm 0.1$	$+0.0 \pm 0.1$
65	$+0.1 \pm 0.3$	$+0.4 \pm 0.2$	$+1.8 \pm 0.7$	VILL	$+1.2 \pm 0.1$	-1.0 ± 0.0	-1.6 ± 0.1
6a	–	–	–		–	–	–
Eb	-1.1 ± 0.3	$+0.3 \pm 0.3$	$+0.8 \pm 2.1$		–	–	–
Ma	$+4.2 \pm 0.2$	$+1.7 \pm 0.2$	$+0.0 \pm 0.6$	MATE	$+3.6 \pm 0.0$	$+3.1 \pm 0.0$	$+0.4 \pm 0.0$
Mc	$+1.8 \pm 0.2$	$+2.1 \pm 0.2$	-3.0 ± 0.8	MEDI	$+2.1 \pm 0.1$	$+2.0 \pm 0.0$	-1.7 ± 0.1
Mh	–	–	–	METS	-2.8 ± 0.0	-0.5 ± 0.0	$+3.8 \pm 0.0$
Nt	$+4.5 \pm 0.2$	-0.1 ± 0.2	-0.4 ± 0.7	NOT1	$+4.4 \pm 0.0$	$+1.0 \pm 0.0$	-1.0 ± 0.0
Ny	$+0.5 \pm 0.6$	-1.8 ± 0.3	$+7.3 \pm 1.5$	NYA1	-1.3 ± 0.0	-10.1 ± 0.0	$+8.0 \pm 0.1$
On	-0.8 ± 0.2	-1.2 ± 0.2	$+2.1 \pm 0.7$	ONSA	-0.9 ± 0.0	-3.3 ± 0.0	$+2.4 \pm 0.0$
Sv	–	–	–		–	–	–
Yb	–	–	–	YEBE	$+0.7 \pm 0.0$	-1.4 ± 0.0	-0.2 ± 0.0
Ys	–	–	–		–	–	–
Zc	–	–	–	ZECK	-4.1 ± 0.1	$+5.1 \pm 0.1$	$+0.9 \pm 0.1$

servation time are main characteristics of the GNSS technique. For the comparison of our results we choose the IGb08 catalogue which is the current reference frame of the IGS and a minor update of the previous IGS08 frame that was derived from an extraction of stable GNSS station coordinates from ITRF2008 (Altamimi et al. 2011) with some minor corrections. The IGS08 set of stations had been selected according to following main criteria: station performance, track record, monumentation, collocation and geographical distribution (Rebischung et al. 2012). For our investigated VLBI stations co-located GNSS antennas in the IGb08 catalogue are found in the vicinity of all stations, except for Effelsberg and Svetloe. In Table 5 (columns six to eight) the velocities of the GNSS sites with respect to station Wettzell (in their local topocentric frames) are summarized applying the same strategy as in the VLBI analysis. In Figs. 11 and 12 the velocities in the horizontal plane and vertical direction, respectively, are plotted together with the velocities of VLBI antennas from our analysis at the common stations. In general, there is a good agreement between both solutions. In the horizontal plane the agreement is within the sub-millimetre per year range at most of the stations. The largest difference and the only one in millimetre range is found at station Zelenchukskaya (6.5 ± 0.1 mm/yr from GNSS versus 10.13 ± 1.28 mm/yr from VLBI in the southeast direction). A similar discrepancy is found in the vertical motion where, as mentioned in Sect. 5.2, the VLBI velocity has a large formal error and it is thus not a very reliable estimate of the real movement of station Zelenchukskaya, which from GNSS analysis is determined as 0.9 ± 0.1 mm/yr with respect to Wettzell.

6 Conclusions

A total number of 114 European VLBI sessions from the last nearly 22 years (1990–2011) is analysed within this work. In a first step the baseline length repeatabilities are determined, where we show that at most of the baselines the repeatability is below 10 mm. The main

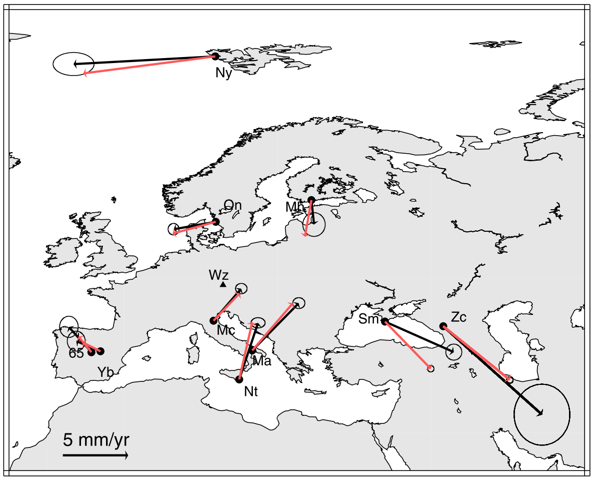

Fig. 11 Horizontal station velocities with respect to Wettzell from European VLBI sessions (*black colour*) compared to GNSS results (*light red colour*). The *ellipses* display the 95 % confidence interval (Color figure online)

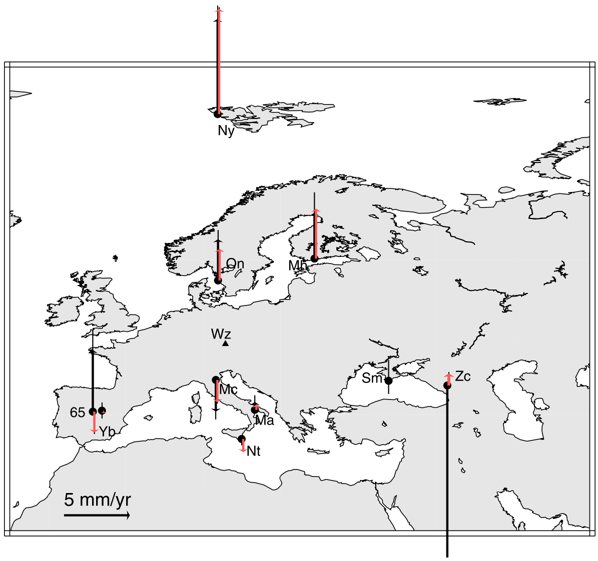

Fig. 12 Vertical station velocities with respect to Wettzell from European VLBI sessions (*black colour*) compared to GNSS results (*light red colour*). The *bars* represent the formal errors (Color figure online)

focus of this paper is the estimation of station velocities within a common global adjustment of all available VLBI sessions, i.e. we estimate station coordinates and velocities together with EOP, troposphere and clock parameters. Comparison of two theoretical global tectonic plate models NUVEL-1A and MORVEL reveals a rotation of 4.3 deg between the models for the European plate. The better agreement between the crustal movement estimated in our study and the MORVEL tectonic plate model (average difference of -1.49 ± 0.67 deg) is found, although the speed of the horizontal motion is faster when estimated by VLBI present-day measurements than predicted from the models covering geological time scales. For NUVEL-1A the discrepancy is 6.3 ± 1.2 % and for MORVEL 11.9 ± 1.2 % of the averaged horizontal motion.

Furthermore, we provide comparison with other analyses of space geodetic data. The differences between our estimates and those presented by Haas et al. (2003) reflect the additional nearly 10 years included in our analysis. Largest differences to the results reported by Haas et al. (2003) are obtained at stations Ny-Ålesund and Crimea for which the number of sessions has more than doubled in the present analysis. By comparing the VLBI crustal motion velocity with the current IGS reference frame (IGb08) estimated by the GNSS technique an agreement in the sub-millimetre per year range is found at most of the stations.

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