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Large-scale strain-rates in Europe derived from observations in the European geodetic VLBI network

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Abstract. Since 1990 the European fixed station geodetic Very Long Baseline Interferometry (VLBI) network has been observing on a regular basis in order to determine surface motion in Europe. During the first years the network was limited to central and southern Europe. With the inclusion of Ny-Ålesund on Spitsbergen and Simeiz on the Crimean peninsula it received valuable extensions to the north and to the east. Today more than 11 years of observations allow the determination of surface motion in Europe with high accuracy.

Baseline measurements between the European geodetic VLBI stations are achieved with an accuracy of better than 2 mm, plus a baseline dependent term of less than one part per billion. Topocentric displacements of the European geodetic VLBI stations are determined with respect to a central reference station. These results show evidence for horizontal deformation due to post-glacial rebound in the northern part of the network. In the southern part of the network the results for horizontal motions display the complex evolution of the Apennines system. The vertical deformations detected in the northern part exceed the predictions due to post-glacial rebound. The subsidence at the station Medicina can be explained by a combination of tectonic processes and man-made influences. The uplift detected at Madrid has no explanation yet, while the other stations do not show significant vertical motion.

Using the derived topocentric displacements, strain-rates in Europe are determined on a large-scale. The results show strain-rates with maximal values of 5.5 ppb/yr which are significantly smaller than those that have been observed in the eastern Mediterranean area. In the Alpine region compressional strain-rates are observed.

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1 Introduction

Although the development of geodetic Very Long Baseline Interferometry (VLBI) was lead by American research groups, observatories in Europe were also equipped with VLBI hardware and participated in intercontinental observing sessions since the seventies and eighties. The Onsala Space Observatory participated as early as 1968 in transatlantic VLBI experiments with the Mark I VLBI system (Scherneck et al., 1998). Later when the Mark III VLBI system was developed and installed, the European geodetic VLBI group (a community formed by members of institutions active in geodetic VLBI) decided to initiate a purely European geodetic VLBI programme on a regular basis. This programme was started in January 1990, and until December 2000, a total number of 59 purely European sessions were carried out. The coordinator of the programme is the Geodetic Institute of the University of Bonn (GIUB), and the observed VLBI data are correlated with the Mark IIIa/IV correlator of the Max-Planck-Institute for Radio Astronomy (MPIfR) in Bonn by members of the Geodetic Institute.

The two main goals of the programme are the determination of surface deformation in Europe with geodetic VLBI and to provide a stable reference network for other geodetic techniques used in the area, e.g. smaller-scale regional Global Positioning System (GPS) networks. Observed surface deformations facilitate the possibility to infer lithospheric deformations, under the conditions that crust and lithosphere form a mechanical unit and the geodetic observations are representative for the crustal deformation. This requires of course a careful monitoring of local footprints at the geodetic observing sites and the corresponding site ties using collocated geodetic techniques.

This multi-national research project causes additional operational costs for the participating institutions due to coordination, scheduling, shipping of magnetic tapes, data pro-

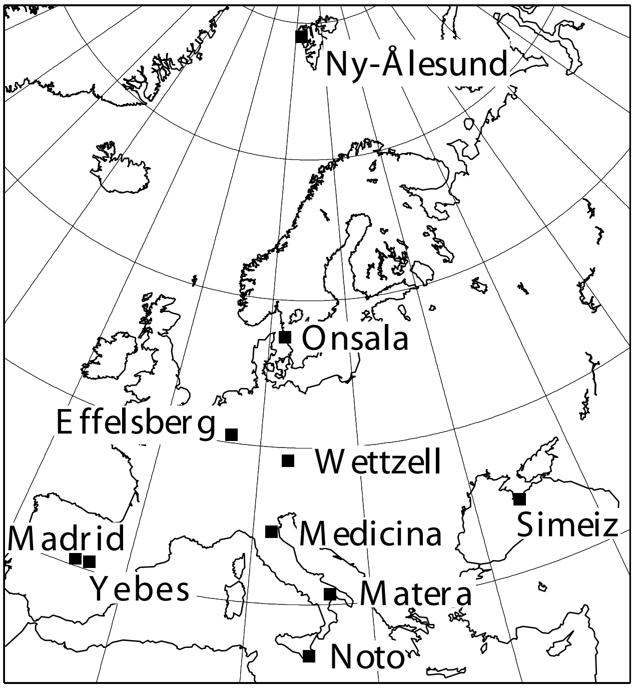

Fig. 1. The fixed station European geodetic VLBI network in 2000.

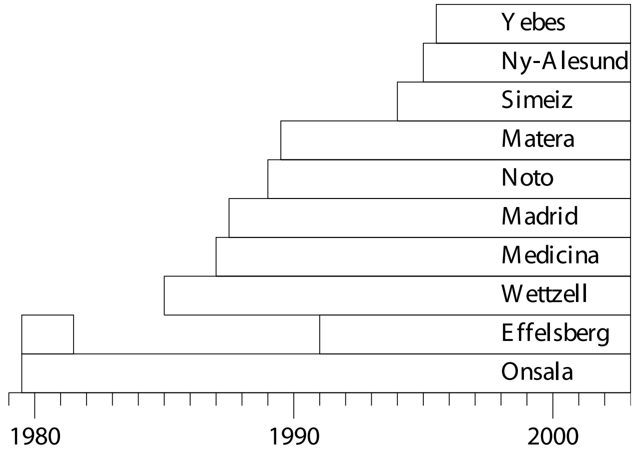

Fig. 2. Temporal evolution of the participation of European VLBI observatories in high precision geodetic observations.

cessing etc. Since these costs are beyond the regular budgets, the European geodetic VLBI group applied for support by the European Commission (EC). During the years 1993–1996 the project received grants from the EC in the "Fourth Framework Programme for Research and Technical Development". The second phase of the project (1996–2000) is supported by the EC in the "Training and Mobility of Researchers" (TMR) programme. The grant includes five temporary post-doctoral visiting researcher positions in four different participating countries. More details on managing and funding the European geodetic VLBI network can be found in Campbell (1995), Campbell (1996), and Campbell (1997).

2 The European geodetic VLBI network

In the year 2000 the fixed station European geodetic VLBI network consisted of 10 stations: Onsala (Sweden), Effelsberg (Germany), Wettzell (Germany), Medicina (Italy), Madrid (Spain), Noto (Italy), Matera (Italy), Simeiz (Ukraine), Ny-Ålesund (Norway) and Yebes (Spain). Table 1 lists the VLBI sites, the size of the telescopes and the operating institutions while Fig. 1 displays the current configuration of the network.

Figure 2 depicts the temporal evolution of the participation of European VLBI stations in high precision geodetic measurements. Pre-requisites for precise geodetic VLBI measurements are that the stations are equipped with a Mark III VLBI system, S/X-band receivers for simultaneous observations at two frequencies to be able to compensate for the ionospheric propagation delay, and a hydrogen maser atomic clock for precise time keeping and frequency generation. In a minimum configuration two radio telescopes forming a baseline are pointed simultaneously at the same extra-galactic radio source, i.e. a quasar, and detect the incoming wave front. Signals in two frequency bands are observed, digitised, and recorded on magnetic tapes together with precise time information by the local frequency standards. Several such observations are performed utilising different radio sources, thus generating different geometries. The magnetic tapes with the recorded signals are sent to a central signal combination facility, called the correlator, where the recorded signals are combined pairwise, thereby forming an interference pattern. The outputs of the correlation process are propagation delays of the observed wave fronts on the individual baselines, which in a further step can be used for geodetic analysis. See Sovers et al. (1998) for more details on the VLBI technique.

The first two European VLBI observatories equipped with Mark III hardware for precise geodetic VLBI measurements were Onsala and Effelsberg which performed their first Mark III observations in 1980. At that time Effelsberg was only supplied temporarily with a Mark III terminal on loan for testing purposes. From 1991 onwards all hardware components for precise geodetic observations were available permanently on-site at Effelsberg and observations were made possible. Nevertheless Effelsberg can only participate once or twice per year in geodetic VLBI sessions since the 100 m telescope is highly demanded for astronomy.

With Wettzell coming on line in late 1984 the first routine observations within intercontinental geodetic VLBI sessions were started. In the late-eighties, the Italian stations Medicina, Noto and Matera and the NASA Deep Space station near Madrid (Spain) were completed. In 1994 the two stations Simeiz and Ny-Ålesund extended the geodetic network to the east and to the north. With the Yebes observatory, an additional observatory in Spain is in line for routine observations in the European network since 1995.

Figure 3 shows pictures of the radio telescopes used in the European geodetic VLBI network. Two of them, the tele-

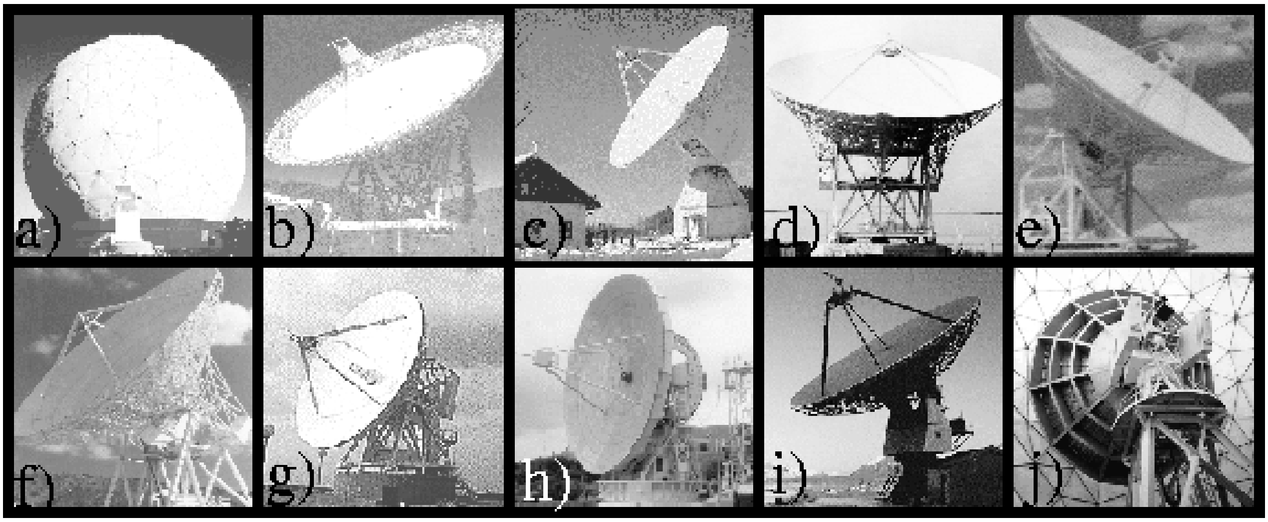

Fig. 3. The radio telescopes of the fixed station European geodetic VLBI network: **(a)** Onsala (20 m), **(b)** Effelsberg (100 m), **(c)** Wettzell (20 m), **(d)** Medicina (32 m), **(e)** Madrid (34 m), **(f)** Noto (32 m), **(g)** Matera (20 m), **(h)** Simeiz (20 m), **(i)** Ny-Ålesund (20 m) and **(j)** Yebes (13.7 m). The telescopes at Onsala and Yebes are enclosed in radomes.

Table 1. European geodetic VLBI stations with name, diameter D of the telescopes and operating institution

Station	D [m]	operating institution
Effelsberg	100.0	Max-Planck-Institut für Radio-Astronomie, Bonn, Germany
Madrid	34.0	Consejo Superior de Investigaciones Científicas (CSIC), NASA Deep Space Communications Complex (MDSCC), Madrid, Spain
Matera	20.0	Instituto di Tecnologia Informatica Spaziale (ITIS), Agenzia Spaziale Italiana (ASI), Matera, Italy
Medicina	32.0	Istituto di Radioastronomia, C.N.R. Bologna, Italy
Noto	32.0	Istituto di Radioastronomia, C.N.R. Bologna, Italy
Ny-Ålesund	20.0	Geodetic Institute of the Norwegian Mapping Authority (GI/NMA), Norway
Onsala	20.0	Onsala Space Observatory (OSO), Chalmers Tekniska Högskola (CTH), Sweden
Simeiz	22.0	Crimean Radio Astrophysical Observatory, Simeiz, Ukraine
Wettzell	20.0	Bundesamt für Kartographie und Geodäsie (BKG) – Fundamentalstation Wettzell, Germany
Yebes	13.7	Centro Astronómico de Yebes, Observatorio Astronómico Nacional, Guadalajara, Spain

scope at Onsala and the telescope at Yebes are enclosed inside radomes to protect the delicate reflector surfaces, because these telescopes are also used for astronomical mm-VLBI observations.

Routine observations in the network started with three sessions each in 1990 and 1991. For the following years six sessions per year were planned. In 1993 only four of them could be observed due to correlator capacity problems. It is planned to increase the number of observation sessions per year from 2000 onwards, given that the necessary correlator capacity is available. Table 2 lists all 59 sessions observed until December 2000 with date and participating stations.

3 The geodynamic situation in the area covered by the European geodetic VLBI network

The area covered by the network extends from the Spitsbergen archipelago in the North to the island of Sicily in the South, and from the Iberian peninsula in the West to the Crimean peninsula in the East. In a geodynamical sense it can be divided into three main units which are the northern, the central, and the southern part.

The northern part of the network encompasses the Spitsbergen archipelago and Fennoscandia. It was covered by a substantial ice sheet in the Pleistocene. Since the vanishing of this ice shield about 10 000 years ago, this area is under glacial isostatic adjustment and reacts with surface de-

Table 2. European geodetic VLBI sessions between January 1990 and December 2000 with the date of observation and the participating stations. The abbreviations for the stations are:

We	= Wettzell (Germany),	On	= Onsala (Sweden),
Me	= Medicina (Italy),	Ma	= Madrid (Spain),
No	= Noto (Italy),	Mt	= Matera (Italy),
Ef	= Effelsberg (Germany),	Mv	= Mobile VLBI unit,
Si	= Simeiz (Ukraine),	Ny	= Ny-Ålesund (Norway),
Ye	= Yebes (Spain),	Ti	= Tigo transportable VLBI station at Wettzell (Germany)

Euro-01	01/26/90	We	On	Me	Ma	No						
Euro-02	05/09/90	We	On	Me	Ma	No	Mt					
Euro-03	20/12/90	We	On	Me	Ma	No	Mt					
Euro-04	06/01/91	We	On		Ma		Mt					
Euro-05	08/09/91	We	On	Me	Ma	No	Mt					
Euro-06	01/12/91	We		Me	Ma		Mt	Ef				
Euro-07	14/01/92	We	On	Me	Ma	No	Mt					
Euro-08	08/04/92		On	Me	Ma	No	Mt					
Euro-09	12/05/92			Me	Ma		Mt					Mv
Euro-10	07/07/92		On	Me	Ma		Mt					Mv
Euro-11	03/11/92	We	On	Me	Ma		Mt					
Euro-12	01/12/92	We	On	Me	Ma		Mt	Ef				
Euro-13	16/02/93	We	On	Me	Ma	No	Mt					
Euro-14	27/04/93	We		Me	Ma	No	Mt					
Euro-15	18/08/93	We	On	Me	Ma		Mt					
Euro-16	11/12/93	We	On	Me	Ma		Mt	Ef				
Euro-17	09/02/94	We		Me		No						
Euro-18	27/04/94	We	On	Me	Ma	No	Mt	Ef				
Euro-19	29/06/94	We	On	Me	Ma	No	Mt					
Euro-20	31/08/94	We	On	Me	Ma	No	Mt		Si			
Euro-21	26/10/94	We	On	Me		No	Mt	Ef	Si	Ny		
Euro-22	28/12/94	We	On	Me	Ma	No	Mt			Ny		
Euro-23	01/02/95	We	On	Me	Ma	No	Mt		Si	Ny		
Euro-24	12/04/95	We	On	Me	Ma	No	Mt	Ef	Si	Ny		
Euro-25	08/06/95	We	On	Me	Ma	No	Mt		Si	Ny	Ye	
Euro-26	31/08/95	We	On		Ma					Ny		
Euro-27	09/11/95	We	On	Me	Ma	No	Mt					
Euro-28	06/12/95	We	On	Me	Ma	No	Mt	Ef		Ny		
Euro-29	07/02/96	We	On	Me	Ma	No	Mt					
Euro-30	25/04/96	We	On		Ma				Si	Ny		
Euro-31	12/06/96	We	On		Ma	No	Mt					
Euro-32	09/09/96	We	On		Ma	No	Mt					
Euro-33	03/11/96	We	On	Me	Ma	No	Mt	Ef		Ny	Ye	
Euro-34	05/12/96	We	On	Me	Ma	No	Mt	Ef		Ny	Ye	
Euro-35	29/01/97	We	On	Me			Mt					
Euro-36	17/03/97	We	On	Me			Mt				Ye	
Euro-37	16/06/97	We	On	Me		No	Mt		Si	Ny	Ye	
Euro-38	25/08/97	We	On	Me		No	Mt		Si	Ny		
Euro-39	30/10/97	We	On	Me	Ma	No	Mt		Si	Ny		
Euro-40	08/12/97	We	On	Me	Ma	No	Mt	Ef	Si	Ny		
Euro-41	02/02/98	We	On	Me	Ma	No	Mt		Si	Ny		Ti
Euro-42	20/04/98		On	Me		No	Mt		Si	Ny		
Euro-43	22/06/98	We	On			No	Mt		Si	Ny		Ti
Euro-44	17/08/98	We	On	Me			Mt		Si	Ny		Ti
Euro-45	12/10/98	We	On	Me	Ma	No	Mt			Ny		
Euro-46	14/12/98	We		Me	Ma	No	Mt	Ef	Si	Ny		Ti

Table 2. continued ...

Euro-47	01/02/99	We	On	Me		No				Ny		Ti
Euro-48	26/04/99	We	On	Me	Ma	No	Mt			Ny	Ye	
Euro-49	28/06/99	We	On	Me	Ma	No	Mt			Ny	Ye	Ti
Euro-50	16/08/99	We	On	Me	Ma	No	Mt			Ny	Ye	Ti
Euro-51	11/10/99	We	On	Me	Ma	No			Si	Ny	Ye	Ti
Euro-52	13/12/99	We	On	Me	Ma	No	Mt	Ef	Si	Ny	Ye	
Euro-53	27/01/00	We	On	Me		No	Mt			Ny	Ye	Ti
Euro-54	07/02/00	We	On	Me		No	Mt			Ny	Ye	Ti
Euro-55	16/03/00	We	On	Me			Mt			Ny		
Euro-56	15/05/00	We	On	Me		No	Mt				Ye	Ti
Euro-57	07/08/00	We	On			No	Mt			Ny		
Euro-58	04/09/00	We	On		Ma	No	Mt			Ny		
Euro-59	07/12/00	We	On	Me	Ma			Ef		Ny		

formation. The centre of the previously glaciated area is mainly affected by vertical deformation (Mitrovica et al., 1994). Horizontal deformation encompasses predominantly the periphery of the former ice shield, at the transition from the central ice dome to the fore-bulge area (Mitrovica et al., 1994). These horizontal deformations are sensitive to the thickness of the lithosphere and the upper mantle viscosity (James and Morgan, 1990), (Mitrovica et al., 1994), (Milne et al., 2001). For the centre area, maximum uplift rates of 12 mm/yr are predicted and the maximal horizontal deformation in the fore-bulge area is predicted to be 2 mm/yr (Mitrovica et al., 1994). The two VLBI stations Onsala and Ny-Ålesund are located in the post-glacial rebound area.

The central part of the network north of the Alpine system can be regarded as the essentially "stable" part of Europe although this part includes a zone of crustal weakness along the Rhine graben (Ziegler, 1992) and shows evidence for light tectonic activity (Vanneste et al., 1999). The two VLBI stations Wettzell and Effelsberg are located in this central part of the network, south of the post-glacial fore-bulge area, and north of the Alpine system.

The southern part of the network encompasses the western Mediterranean region. The evolution and dynamics of the Mediterranean area have been described by Mueller and Kahle (1993). According to Réhault et al. (1984), Dewey et al. (1989), Albarello et al. (1995) and Gueguen et al. (1998), the western part is dominated by the evolution of the Maghrebides-Apennines system and its related back-arc basin. However, the driving mechanism is still controversial. When the subduction of the European margin under the Alps reached the collision stage, a flip of subduction resulted (Doglioni et al., 1997), (Gueguen et al., 1998). The Apennin subduction began, starting at the front of the back-thrust belt of the Alps. At first, the Apennin subduction quickly migrated eastward. But when the Apenninic front reached the thicker continental crust of the Apulia Platform at about 10 Ma ago, a drastic change of the geodynamic setting of the Apennin system followed. The migration of the subduction hinge slowed down in the southern Apennines, whereas in the central and northern Apennines, the subduction of thin Adriatic lithosphere is still ongoing and allows a roll-back of the hinge (Gueguen et al., 1998). Due to these different migration rates, the Apennines front was split in two "subarcs". Therefore the precise determination of the motion of the Adriatic plate is fundamental to understand the present-day evolution of the Apennines system. Five of the European geodetic VLBI stations are located in the western Mediterranean region.

4 Data analysis and results for crustal motion

The European geodetic VLBI sessions from 1990 to mid 2000 were analysed with the VLBI data analysis software package CALC/SOLVE/GLOBL (Ma et al., 1990). The analysis strategy used is a so-called "baseline-solution" and is described by Haas et al. (2000). Each observation session is treated separately in a least squares adjustment and station coordinates are estimated for each station participating in the session. VLBI is a differential technique observing quasars at effectively infinite distance of the earth (Sovers et al., 1998). Therefore the coordinates of a reference station have to be kept fixed in the adjustment of the observations. Additionally, the earth rotation parameters have to be fixed to permit the estimation of all other station coordinates. For the analysis we adopted earth rotation parameters of the EOP(IERS) C04-series of the International Earth Rotation Service (IERS) (IERS C04, 2000) together with radio source positions from a recent global VLBI solution (NASA GSFC, 1999).

A time series of geocentric station coordinates results from the individual least squares adjustments and allows to compute the baseline components between individual stations for each epoch. The time series of baseline lengths and baseline components gives insight into the repeatability of the measurements and the quality of the individual sessions. Topocentric station drifts components can be inferred from the time series of geocentric station coordinates.

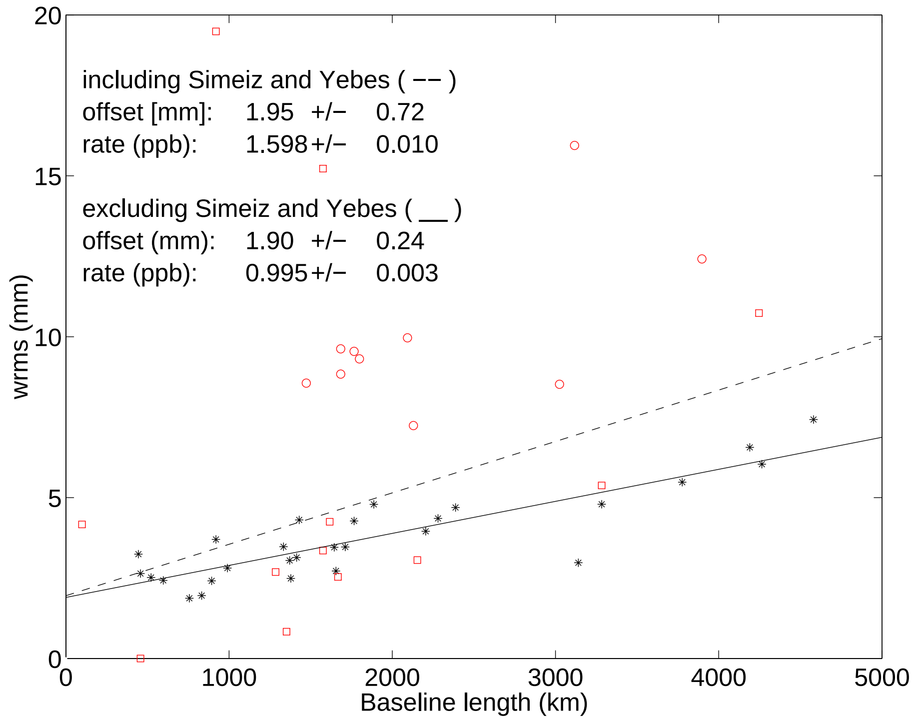

Fig. 4. Baseline length repeatability in the European geodetic VLBI network. Baselines involving Simeiz are depicted with circles, those involving Yebes are depicted with squares, all other baselines are marked with asterisks. The regression line including the baselines with Simeiz and the baselines with Yebes is shown as dashed line while the regression line excluding baselines with the two stations is depicted with a solid line.

Table 3. Baselines to Wettzell: number of observation sessions n, baseline length l in [km], baseline length rate r in [mm/yr] with standard deviation, weighted root-mean square error (wrms) in [mm] and relative accuracy a in [ppb]

Baseline	n	l	r	wrms	a
Wettzell–Effelsberg	13	457	-1.4 ± 1.0	2.7	5.9
Wettzell–Medicina	46	522	-2.2 ± 0.4	2.5	4.5
Wettzell–Onsala	51	919	-0.6 ± 0.3	3.7	4.0
Wettzell–Matera	48	990	-3.7 ± 0.3	2.8	2.8
Wettzell–Noto	42	1371	-4.5 ± 0.4	3.1	2.3
Wettzell–Yebes	13	1575	$+0.8 \pm 2.2$	3.4	2.2
Wettzell–Madrid	41	1655	$+0.2 \pm 0.4$	2.7	1.6
Wettzell–Simeiz	18	1684	$+0.8 \pm 7.7$	8.8	5.2
Wettzell–Ny-Ålesund	31	3283	$+0.9 \pm 1.2$	4.8	1.5

The baseline length results have the advantage of being, to first order, invariant to changes of the earth orientation parameters (EOP). Thus, any precise EOP series is a sufficient basis if only baseline lengths are considered. This is not true if topocentric station coordinates and their evolution are inferred from the geocentric coordinates since in that case the particular EOP series affects the orientation of the network. Therefore small rotations about the reference point that was fixed in the solution are introduced. This effect scales with the extension of the network. The European network is rather small compared to intercontinental networks and therefore it is appropriate to adopt Earth orientation parameters from the IERS for the purpose of our analysis.

4.1 Baseline length results and their evolution

There are 45 baselines in the network with baseline lengths between 99 and 4580 km. For each baseline the baseline evolution has been calculated by linear regression of individual determinations. Figure 4 displays the repeatabilities of the baseline measurements. They are shown as weighted root-mean square errors (wrms) of the regression lines for baseline evolution against the corresponding baseline length. Baselines including the stations Yebes and Simeiz show significantly worse repeatabilities than the other baselines. Both stations have rather a short observation history and suffered from many technical problems which explains their low performance. When excluding the baselines that include Yebes and Simeiz, the repeatability of baseline measurements in the European geodetic VLBI network is as good as 1.9 mm plus an additional term depending on the baseline length of less than one part per billion (ppb).

The station Wettzell has been used as a reference station for the analysis, due to its central position in the network. Table 3 shows the results for all baselines including Wettzell, with the number of observation sessions per baseline, the baseline length, the baseline length rates and their standard deviations, the wrms of the regression lines, and the relative accuracy in parts per billion. Figure 5 displays the individual

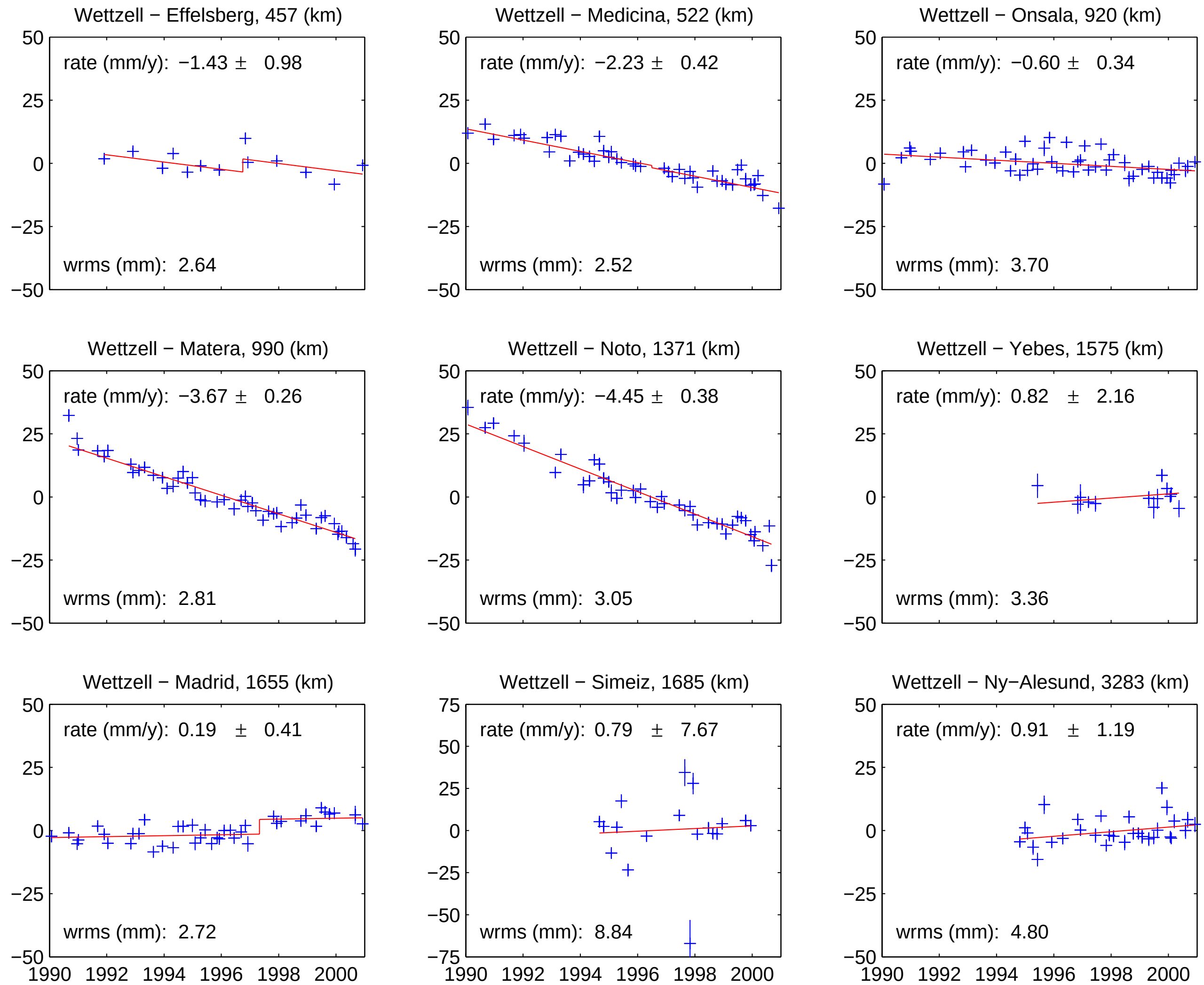

Fig. 5. Baselines in the European geodetic VLBI network including Wettzell and their temporal evolution.

observations and the corresponding regression lines. Since there have been track and wheel replacements at the three stations Medicina, Effelsberg, and Madrid, discontinuities in the baseline length evolution have been introduced at these times and the corresponding offsets have been estimated together with the regression lines. It can be seen that the baselines with sufficient long observation history give excellent results, with significant baseline length rates and low wrms values.

4.2 Topocentric station movements

In addition to the baseline length results, we also determined topocentric station drift components. The least squares adjustment of the VLBI data set yielded a time series of geocentric station coordinates for all stations involved except the reference station. In order to refer all results to a single reference station we had to exclude three sessions in 1992 and one in 1998 from the analysis, since they do not include data of Wettzell which we used as reference station. The global drift of the European plate was subtracted from the individual station coordinates according to the NUVEL-1A-NNR plate tectonic model (De Mets et al., 1994). Thus, the station coordinates were referred to a European fixed system. Transformation from Cartesian into ellipsoidal coordinates yielded time series for each station for east and north component and ellipsoidal height. These time series were then used to determine horizontal and vertical station velocities with respect to the Eurasian plate. Fixing the motion of one site to a continental drift model such as NUVEL-1A-NNR, and using high accuracy Earth rotation parameters from external sources such as the EOP(IERS) C04-series of the International Earth Rotation Service (IERS) (IERS C04, 2000) places a reliable bound on the long term drift of the European continent as represented by the observing sites. Only the Earth rotation parameters have an effect on the determination of the drifts of the stations relative to Wettzell. Since the long term stability of Wettzell appears to be extremely reliable from global solutions (NASA GSFC, 1999) and the short term variations only increase the scatter of the results, the drift vectors deserve a high level of confidence. Table 4 lists the results for topocentric velocities which are also

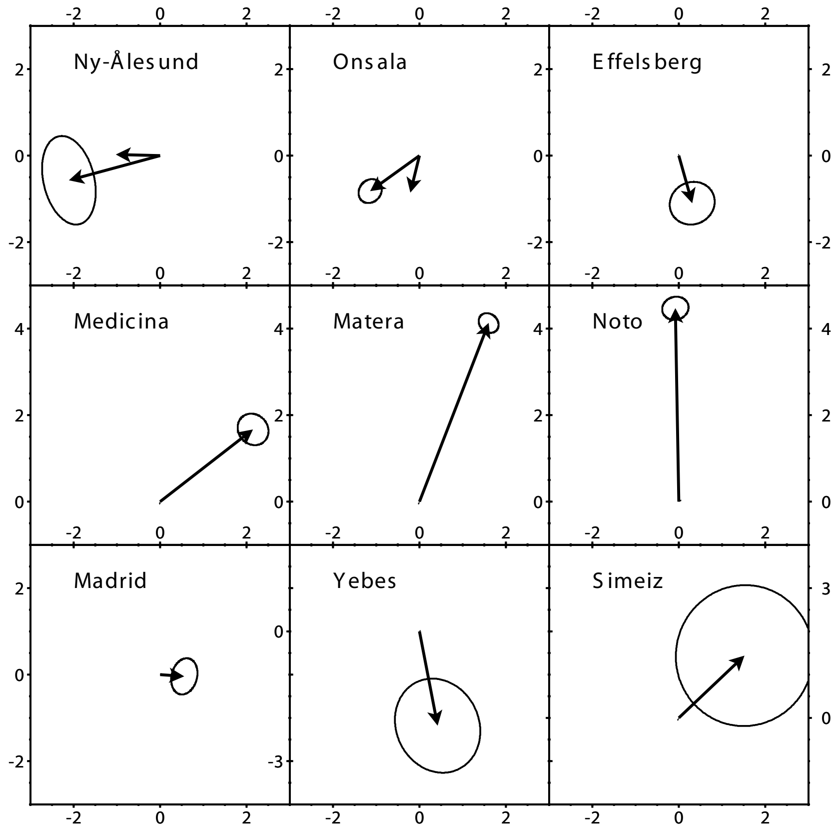

Fig. 6. Observed horizontal motions in [mm/yr] with respect to Wettzell are shown as vectors with error ellipses. For Ny-Ålesund and Onsala the PGRM predictions (see text) are depicted as vectors without error ellipses.

Table 4. Horizontal and vertical velocities in [mm/yr] and weighted root-mean square error (wrms) in [mm] observed in the European geodetic VLBI network

Station	east	wrms	north	wrms	vertical	wrms
Effelsberg	$+0.3 \pm 0.3$	2.5	-1.1 ± 0.4	3.0	$+1.0 \pm 2.6$	10.8
Madrid	$+0.6 \pm 0.2$	3.1	0.0 ± 0.3	3.2	$+2.0 \pm 0.8$	13.2
Matera	$+1.6 \pm 0.1$	2.4	$+4.1 \pm 0.2$	2.5	$+0.2 \pm 0.6$	11.1
Medicina	$+2.1 \pm 0.2$	2.1	$+1.7 \pm 0.3$	2.2	-2.7 ± 0.9	7.7
Noto	-0.1 ± 0.2	3.0	$+4.5 \pm 0.2$	3.1	-0.5 ± 0.7	8.6
Ny-Ålesund	-2.1 ± 0.4	4.8	-0.6 ± 0.7	4.4	$+5.9 \pm 1.8$	13.8
Onsala	-1.1 ± 0.2	2.6	-0.8 ± 0.2	3.3	$+1.8 \pm 0.7$	15.4
Simeiz	$+1.5 \pm 1.1$	7.3	$+1.4 \pm 1.1$	2.9	-0.8 ± 4.5	40.1
Yebes	$+0.4 \pm 0.7$	4.1	-2.2 ± 0.7	3.2	$+1.1 \pm 3.3$	13.9

shown in Fig. 6 and Fig. 7. The figures also show predictions of topocentric velocities due to post-glacial rebound. These values were calculated using the ice model by Tushingham and Peltier (1991) and applying the formalism of Mitrovica et al. (1994). A lithospheric thickness of 120 km was used, elasticity and density of the PREM model (Dziewonski and Anderson, 1981) were adopted, and values of 1.0×10^{21} Pas and 2.0×10^{21} Pas were used for the viscosities of the upper and lower mantle, respectively. The sea-level equations have been solved according to the suggestions by Mitrovica and Peltier (1991), however using mobile coast-lines, which were iterated at each time step (1 kyr) by constraining the available oceanic water. In the following these predictions will be referred to as post-glacial rebound model (PGRM) predictions. Since the observed motions are with respect to Wettzell, for consistency purposes also the PGRM predictions are calculated with respect to Wettzell.

The two northern stations Ny-Ålesund and Onsala show horizontal motions relative to Wettzell that are deviating from the PGRM predictions. Ny-Ålesund and Onsala move

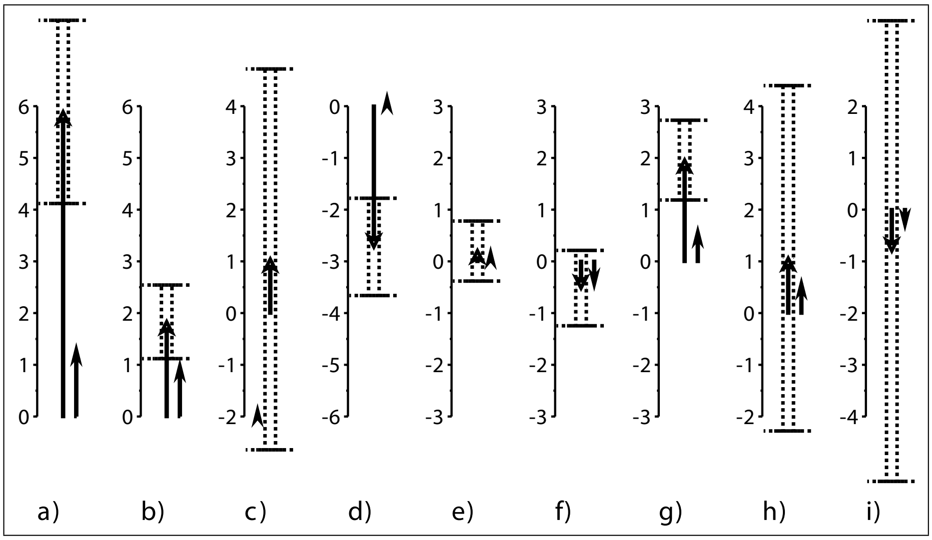

Fig. 7. Observed vertical motions in [mm/yr] with respect to Wettzell are shown as vectors with error bars. PGRM predictions (see text) are depicted as vectors without error bars. The stations are: **(a)** Ny-Ålesund, **(b)** Onsala, **(c)** Effelsberg, **(d)** Medicina, **(e)** Matera, **(f)** Noto, **(g)** Madrid, **(h)** Yebes and **(i)** Simeiz.

by 2.2 ± 0.4 mm/yr with azimuth 254.0 ± 17.9° and by 1.4 ± 0.2 mm/yr with azimuth 234.0 ± 8.4° with repect to Wettzell, while the PGRM predictions are 1.0 mm/yr with azimuth 271.5° and 0.9 mm/yr with azimuth 193.9°, respectively. For Ny-Ålesund the magnitude deviates more than the direction, whereas for Onsala the direction deviates more than the magnitude.

Madrid does not show significant horizontal movement with respect to Wettzell, indicating that currently there is no larger tectonic motion between central Europe and the Iberian peninsula. The observed horizontal movement of Yebes is not to be regarded as significant due to the low performance of this station.

The determination of horizontal movements for Effelsberg and Simeiz suffers from a restricted number of observations for the first site, and from poor measurement accuracy for the second site. Nevertheless the horizontal motion of Effelsberg appears to be significant from zero, showing a movement of 1.1 ± 0.4 mm/yr with azimuth 164.7 ± 15.5°.

The Italian stations show the largest horizontal site motions in the European geodetic VLBI network. From south to north the magnitude and direction of motion with respect to Wettzell changes and indicates different geodynamic situations. Noto appears to be strongly affected by the African convergence moving northward by 4.5 ± 0.2 mm/yr with azimuth 358.7 ± 2.5°. Matera shows evidence to represent the displacement of the Adriatic plate with a motion of 4.4 ± 0.2 mm/yr with azimuth 21.3 ± 1.5° with respect to Wettzell. The Medicina station is situated in the Po valley right on the front of the Apennines and in a complex geodynamic situation. This station shows a motion of 2.7 ± 0.2 mm/yr with azimuth 51.0 ± 5.6° with respect to Wettzell.

Ny-Ålesund shows a large uplift of 5.9 mm/yr with respect to Wettzell while the PGRM prediction relative to Wettzell is only 1.3 mm/yr. Further investigations are necessary to confirm a possible local or regional reason for this large uplift rate. The uplift of 1.8 mm/yr detected at Onsala is also larger than the the PGRM prediction of 1.0 mm/yr.

The results for vertical motion of Effelsberg, Simeiz and Yebes have still large standard deviations due to low number of observations and technical problems, respectively, and are not statistically significant.

The detected subsidence at Medicina can be explained by a combination of tectonic processes and man-made influences. This area underwent a strong subsidence of up to 1.6 mm/yr during the last 5 Ma (Doglioni, 1994) and suffered from extraction of ground water and gas in the Po valley (Tomasi et al., 1997), even if these effects have been reduced in recent years (Zerbini et al., 2001). The two other Italian stations, Matera and Noto, do not show statistically significant vertical site displacements.

The uplift at Madrid most probably does not have any tectonic but rather a local explanation. An uplift of only about 0.6 mm/yr relative to Wettzell can be explained by the PGRM predictions.

For the VLBI data analysis we assumed zero vertical motion at Wettzell and all vertical results given are relative to Wettzell. Any "real" vertical motion at Wettzell, which cannot be excluded, has to be taken into account if one wants to derive absolute vertical changes. However, we do not expect Wettzell's vertical motion to be any larger than 0.5 mm/yr from precise spirit levelling of the German survey authorities (Schlüter, pers. communication, 1999). The PGRM prediction for Wettzell is a slight subsidence of 0.12 mm/yr and has been taken into account for the calculation of the PRGM

Table 5. Topocentric displacements in [mm] due to track and wheel repair at the stations Medicina, Effelsberg and Madrid

Station	date	east	north	vertical
Medicina	1996.07.01	-3.3 ± 2.3	2.3 ± 2.5	11.7 ± 9.2
Effelsberg	1996.10.01			16.0 ± 18.4
Madrid	1997.04.30		-12.8 ± 3.0	

Table 6. Annual signals in station displacements. The amplitudes α are in units [mm] while the phases ϕ are in units [day of year]

Station	east		north		vertical	
	α	ϕ	α	ϕ	α	ϕ
Madrid	-	-	-	-	4.9 ± 2.7	187 ± 32
Matera	-	-	1.2 ± 0.6	246 ± 30	5.6 ± 2.2	93 ± 22
Medicina	-	-	1.3 ± 0.5	318 ± 24	4.0 ± 2.0	157 ± 27
Noto	-	-	-	-	3.2 ± 2.4	137 ± 44

Table 7. Large-scale strain-rates in Europe. The eigenvalues $\dot{e_1}$ and $\dot{e_2}$ of the strain-rate tensor are given in units [ppb/yr], the azimuth of the strain-rate ellipse θ is given in [°]

Triangle and stations included				$\dot{e_1}$	$\dot{e_2}$	θ
1	Ny-Ålesund	Onsala	Madrid	3.65±0.72	−0.12±0.15	25.66±5.10
2	Ny-Ålesund	Onsala	Effelsberg	1.47±1.08	0.35±0.53	24.07±29.80
3	Ny-Ålesund	Simeiz	Wettzell	0.58±0.47	−0.18±0.56	27.81±37.50
4	Ny-Ålesund	Simeiz	Onsala	0.45±0.40	−0.20±0.68	272.60±65.13
5	Onsala	Wettzell	Madrid	1.01±0.29	−0.72±0.14	13.26±6.09
6	Onsala	Wettzell	Effelsberg	−0.23±0.42	−1.03±0.61	303.34±51.06
7	Onsala	Simeiz	Wettzell	0.47±0.64	−0.89±0.54	16.93±17.28
8	Effelsberg	Madrid	Wettzell	0.04±0.26	−2.51±0.85	335.52±9,90
9	Effelsberg	Wettzell	Medicina	−1.45±0.59	−4.19±0.68	27.43±10.10
10	Wettzell	Medicina	Madrid	2.91±0.29	−3.98±0.58	8.08±2.56
11	Wettzell	Matera	Medcina	−3.62±0.19	−5.47±0.76	71.44±43.50
12	Wettzell	Simeiz	Matera	0.28±0.66	−4.77±0.43	12.06±4.21
13	Medicina	Noto	Madrid	1.44±0.18	−4.15±0.21	328.63±1.54
14	Medicina	Matera	Noto	3.37±0.65	−4.36±0.27	328.91±2.36
15	Simeiz	Noto	Matera	0.43±0.58	−2.71±0.89	301.04±16.87

predictions relative to Wettzell. In any case, for the strain-rate analysis presented later, the important information is the relative motion.

4.3 Station displacements due to track and wheel repair and annual signals

As already mentioned earlier, it was necessary at the three stations Medicina, Effelsberg, and Madrid to repair the tracks and wheels on which the telescopes run. This caused abrupt displacements of the stations. Therefore we included discontinuities for the analysis of topocentric drift rates and estimated the corresponding displacements from the geodetic VLBI data itself. Table 5 shows the estimated displacements that have been tested to be statistically significant.

Furthermore we introduced annual signals in the analysis of topocentric station drifts. Since VLBI telescopes are large metal and metal-reinforced concrete constructions, there can be thermal deformation effects with a predominant annual behaviour. Climate related phenomena may also have effects on the station positions, associated to an annual signature. Table 6 lists the estimated annual signals that were tested to be statistically significant, annual amplitudes α in [mm] and the corresponding phases ϕ in [day of year] are given.

4.4 Large-scale strain-rate analysis

Based on the derived topocentric station movements, we determined large-scale strain-rates in Europe. For this purpose the network was split up into individual finite triangle elements each constructed by three nearby stations (Altiner, 1996). The station Yebes was left out from these calculations

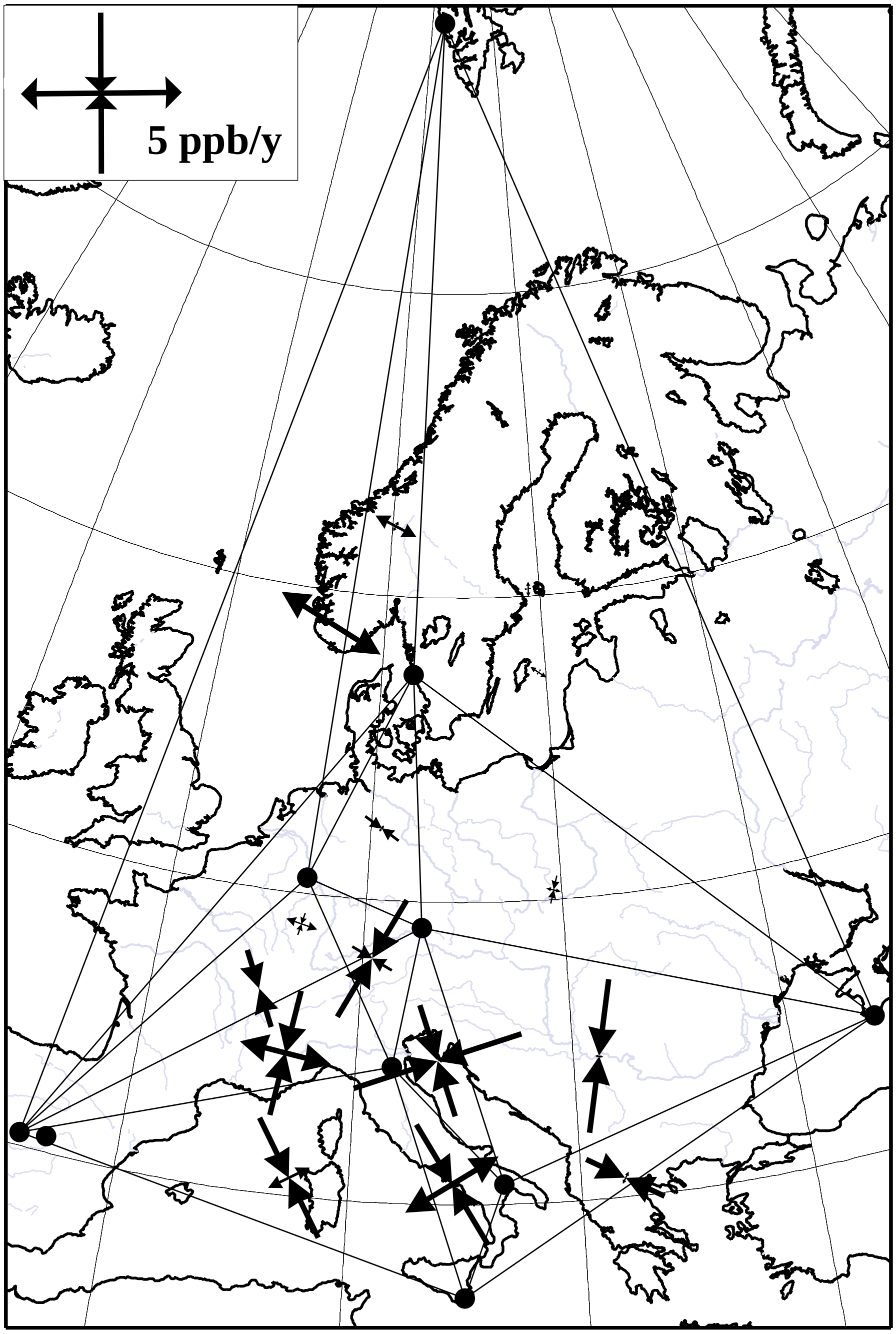

Fig. 8. Large-scale strain-rates in Europe observed with the European geodetic VLBI network.

due to its low performance. The three-dimensional surface strain-rate tensor in each finite triangle was calculated using the three-dimensional topocentric station displacements of the corner stations, the covariant metric tensor of the geographical coordinates and the corresponding Christoffel symbols. The "tangential" part of the three-dimensional surface strain-rate tensor was then transformed into a local Cartesian coordinate system on the reference ellipsoid with origin in the centre of each finite element. The eigenvalues of the tangential surface strain-rate tensor and the orientation of the strain-rate ellipse were calculated for each finite element, see Table 7 and Fig. 8. Standard deviations of the strain-rate parameters were calculated using the standard deviations of the topocentric station motions of the three corner stations of each finite element.

None of the derived strain-rates does exceed 5.5 ppb/yr. The observed strain-rates in the European geodetic VLBI network are significantly smaller than those that have been observed in the eastern Mediterranean for example by campaign based observations using GPS (Kahle et al., 1999). The largest strain-rate is of compressional type with 5.47 ppb/yr and is detected in the triangle #11 (Wettzell, Matera, Medicina). The three triangles #6 (Onsala, Wettzell, Effelsberg), #9 (Effelsberg, Wettzell, Medicina) and #11 (Wettzell, Matera, Medicina) show only compressional strain-rates. In contrast, the triangle #2 (Ny-Ålesund, Onsala, Effelsberg) shows only extensional strain-rates. All other triangles show both type of strain-rates. The strain-rates are extremely small in the northeastern part of the network while they are largest in the central and western Mediterranean of the network. The strain-rates are determined with uncertainties of 10% to 30% in triangles including stations with well determined topocentric motion. Triangles including stations with less well determined topocentric motions give strain-rate results with uncertainties in the range of 60% to 90%, or not statistically significant at all.

5 Discussion and comparison to independent results

The strain-rates observed with the European geodetic VLBI network represent integrated values over large areas of finite triangles that contain different tectonic structures. Thus, it is difficult to compare our results to smaller scale strain-rate observations from other geodetic techniques or even local stress from geological observations.

Our results for maximum strain-rates are on the level of 4–5 ppb/yr in the triangles formed by the Italian stations and Wettzell. This is in contradiction to the result of 13 ppb/yr extensional strain-rate from VLBI observations in the triangle formed by the three Italian stations as reported by Ward (1994). The study by Ward (1994) used only VLBI data until end of 1993 and therefore suffers from too few observations for the Italian stations in order to represent reliable and significant results. On the other hand, there is good agreement between our results for this region and the value of 4.1 ± 0.8 ppb/yr for Italy published by Ward (1998). The results by Ward (1998) have been obtained from a combined analysis of VLBI, GPS and Satellite Laser Ranging (SLR) results provided by international contributors. Devoti et al. (2000) give strain-rate results from an Italian GPS network of 5–10 ppb/yr for the Tyrrenian region. Their results agree quite well in magnitude and orientation with our results.

In the western Mediterranean area we observed strain-rates on the level of 2–4 ppb/yr in triangles formed by Spanish, Italian and central European stations. Ward (1998) obtained a value of 3.2 ± 1.0 ppb/yr for this area which is in agreement with our results. Calais (1999) reported a maximum strain-rate of 30 ppb/yr from three years of continuous GPS measurements in the western Alps, thus contradicting the results by Ward (1998) and our results. The results by Calais (1999) might indicate a smaller-scale tectonic feature in that area which is not resolved from the other solutions.

The comparison of geological stress observations with the strain-rates derived from space geodetic methods faces the difficulty of comparing local observations with large-scale integrated values. The World Stress Map (WSM) (Müller et al., 2000) gives local stress directions and stress regimes, but no magnitudes. The comparison to geodetic strain-rates is restricted to directions and common features in the stress and the strain-rate fields. Grünthal and Stromeyer (1992) present the stress pattern in central Europe in a broad sense, displaying trajectories of maximum horizontal stress. They describe a NW-SE directed compression in western central Europe and a fan-like pattern of compressive stresses at right angle to the arc of the Western Alps. To some degree we can detect similar directions from our strain-rate results.

6 Conclusions and outlook

The European geodetic VLBI network has now been operating for more than 11 years, and has matured to a reliable and highly accurate geodetic observing network. Baseline measurements are possible with a measurement accuracy of 1.9 mm, plus an additional term depending on baseline length of less than 1 ppb. Remarkable results are achieved for horizontal and vertical station motions, that are used to determine the large-scale strain-rate field in Europe. The results can be used to infer upper bounds on present-day tectonics in Europe in the area covered by the VLBI network. We observe maximum strain-rates on the level of 4–5 ppb/yr with uncertainties in the range of 10–20%.

Since VLBI is a precise technique using stable instruments and having a long observational history, it may serve as a precise reference for the geodetic densification in Europe on regional and local scale. Strain-rate analysis for Europe can be improved from combinations of different space geodetic techniques, of VLBI and the much denser spaced GPS networks. Work is in progress to combine the results from European geodetic VLBI with results from continuous GPS networks like the BIFROST project in Fennoscandia (Scherneck et al., 2001).

At present, improvement of the accuracy of the VLBI measurements is continuing. Investigations are concerned with optimising the equipment, the observing strategies, the refraction models and the analysis methods. This includes the geodetic monitoring of the telescope reference points, application of atmospheric loading effects and corrections due to thermal deformation of the radio telescopes.

In the future we hope to extend and densify the European geodetic VLBI network. In particular a further extension to the east and the north is desirable. Existing or planned astronomical VLBI stations in that area, like Metsähovi (Finland), Svetloe (Russia), Torun (Poland), and Irbene (Latvia) may be good candidates. This would allow a better tie to the stable eastern part of the European plate, and an improved determination of post-glacial rebound effects. The Metsähovi station is currently being upgraded and will be able to participate in the observations in 2002 (Pounonen, pers. communication, 2001). Also a densification in the southern part is desirable. Construction work of a new radio-telescope on the island of Sardinia (Italy) has already started and the inclusion of this new station will strengthen the network in the western Mediterranean area.

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