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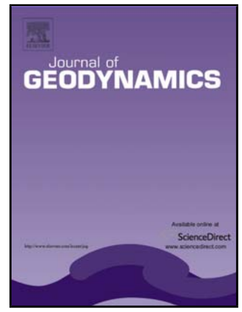

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Intra-plate Deformation in West-central Europe

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Abstract

The central part of Europe north of the alpine orogenic belt is generally seen as a relatively stable area of the western tip of the Eurasian plate. Indeed, up to now, no geodetically significant motions have been detected although an active rift systen running roughly in SSE – NNW direction along the Rhine valley could have some effect on the stability of this region. Presently, the increasing accuracy of geodetic point motions should allow the study of small motions at levels down to nearly 0.1 mm/yr. We start our investigation with a closer look at the 'true' accuracy and significance of GPS derived point velocities of permanent stations. We compare and discuss the different levels of formal errors obtained by the three analysis centers considered in this study (EPN, JPL and SOPAC) and present additional ways of assessing the accuracy using the redundancy offered by different independent analyses and multiple systems operating at one site. On the average, all results indicate that a one sigma level of ±0.3 mm/yr can be seen as a conservative estimate for the horizontal accuracy of point motions in central Europe. On the basis of this assumption we find that at present, the actual velocity field as determined by different analysis groups and centers does not show any significant East-West extensional deformation. We do however see a prominent North-South compressional velocity gradient of about 1mm/yr/1000km (1 nanostrain/yr) which could be associated with the Alpine thrust in conjunction with a south-directed horizontal component of the Fennoscandian Glacial Isostatic Adjustment.

Keywords: Geodetic space techniques, GPS time series, crustal deformation

1. Introduction

In the global scenario of plate tectonics, the continent of Europe at the western end of the Eurasian plate bears its share of crustal deformation: geodetic space techniques and GPS data from permanent stations in particular have been showing prominent site motions on the order of several cm/yr in the Eastern Mediterranean (Turkey and the Aegeis) and on the Mid-Atlantic Ridge (Iceland). The increasing quality and quantity of data in combination with improved analysis systems now also allows to resolve smaller motions down to the millimeter-level and below. A prominent example is given by the observed pattern of horizontal displacements in the range of 0.1 to 2.5 mm/yr due to the Glacial Isostatic Adjustment (GIA) in Fennoscandia (Scherneck et al. 2002). If we narrow our focus to the central area of western Europe, a cursory look at the velocity field does not seem to show any significant motional trends (Altamimi and Legrand 2005): central parts appear more or less stable. Geological evidence, however, does present seismo-tectonic activity, in particular on the Cenozoic Rift System which constitutes a zone of crustal weakness extending from the Alps along the Rhine towards the North Sea **(Fig. 1)**. Geologically inferred deformation rates range from average values over about 20 Ma of 0.005 mm/yr to about 1 mm/yr in shorter active phases (Ahorner 1968, Meghraoui et al. 2000).

Some earlier studies have reported signs of relative point motion in west-central Europe at the level of several tenths of mm/yr, but – as stated by the authors - the data which covered 4 to 6 years of daily GPS observations in the early years of the IGS (1993 – 2000) did not seem to be reliable enough to firmly support such claims (Nocquet et al. 2001). In their follow-up paper (Nocquet and Calais 2003) they state that a level of 0.6 mm/yr (1σ) would approximately draw the limit of significance for site velocities in this area. Similarly, the results of the BIFROST GPS campaign in Scandinavia as published in 2002 can be cited to document a realistic detection limit for GPS derived velocities at that time: the agreement between the observed and modeled motions calculated from tables 2 and 3 in (Scherneck et al. 2002) in terms of RMS is $\sigma(v_{east}) = \pm 0.518$ and $\sigma(v_{north}) = \pm 0.623$ mm/yr. These RMS deviations include the entire GPS error budget as well as GIA model imperfections and local site motions. Considering more recent results on a smaller area of southern Sweden, a set of 12 homogeneously equipped GPS stations with 8 years of 'good' data has produced residual velocity RMS values of $\sigma(v_{east}) = \pm 0.11$ and $\sigma(v_{north}) = \pm 0.14$ mm/yr (Lidberg et al. 2007). This may certainly be seen as the optimum achievable today.

At present, many of the long standing IGS reference stations as well as some stations from other networks have observational records of ten to fifteen years. The increasing length of time series should have significantly reduced the effects of systematic errors and periodicities in the data. Therefore, it seems appropriate to reconsider the available data and provide an updated picture of crustal motions in the central part of western Europe. In Tab 1 we show a list of central European stations that have been selected for the present study.

We like to add that another motivation for specifically studying the central western part in this publication is due to the fact that we have been carrying out regular campaign style GPS measurements in a section of the Lower Rhine Embayment and the adjacent Rhenish Massif (Campbell et al. 2002). This project has been primarily aimed at monitoring mining subsidence but also includes the investigation of tectonic motions connected with the Eifel-Ardennes uplift and horizontal extension on the northern part of the Cenozoic Rift System. First results from 8 annual campaigns (1993-2000) show a small SW – NE extensional motion for two pairs of stations in the Rhenish Massif across the Lower Rhine Embayment of ~0.5 ± 0.5 mm/yr, a possible trend that is still buried in the noise. The annual campaigns are continuing in an extended net of sites providing results from a time span of more than 15 years (Görres 2008).

2. Accuracy of GPS derived site velocities

At the site velocity level of 1 mm/yr and below, the well known systematic errors endemic in geodetic Global Navigation Satellite Systems (GNSS) are causing growing problems. Without going into too much detail we list the most important error types (Zhang et al. 1997, Nikolaidis 2002, Steigenberger et al. 2006), noting that the *changes in time* of these sources are most harmful: reference frame realizations (changes of), satellite orbits (changes, improvements), atmospheric delay (new models), antenna calibration (changes, new standards), multipath environment (changes in antenna setup, neighboring structures). If we focus our attention on the detection of crustal motion we also have to consider ground movements of local origin as well as regional effects such as atmospheric loading and hydrological variations.

While research on each one of these error sources is going on, it is also appropriate to make use of the redundancy and variety of analyses from different groups and centers, the results of which are often publicly available. Certainly the most important outflow of these activities may be seen in the realization of the International Terrestrial Reference Frame (ITRF) which combines all the information contained in the individual results into one consistent global product (Altamimi et al. 2007). The ITRF includes site cordinates at a reference epoch as well as site velocities together with their respective errors (variance/covariance information).

Normally, it would be sufficient to use these errors and discuss the listed site velocities in terms of their geotectonic significance. If we are faced, however, with a rather small subset of sites that seem to be moving randomly at rates between 0.1 and 1 mm/yr, it is necessary to examine more closely each one of these sites and try to establish the quality and consistency of both the data and the subsequent analysis. To a certain degree, this has of course been done in the compilation of the successive ITRF realizations, although some particular aspects or problems of the individual analyses require closer examination in deeper studies. Thus, for the present investigation, we examine several separate solutions *before* the global combination takes place. For ease of data access we chose results from GPS analyses of three different organisations, i.e. the European Permanent Network (EUREF EPN), the JPL Flinn analysis and the SOPAC data center **(Tab. 1a)**. These results have a high degree of independency because they are produced with entirely different software systems and follow their own particular analysis strategy. In addition, we will briefly address recent results of analyses of European VLBI observations (Campbell and Nothnagel 2000) carried out at our institute (IGG).

Tab. 1a: Data sources.

Data Source	Institution	Access	Analysis software
EPN – GPS	EUREF Permanent Network	www.epncb.oma.be	Bernese GPS
JPL - GPS	JPL Flinn Analysis	sideshow.jpl.nasa.gov	GIPSY
SOPAC-GPS	Scripps Orbit and Permanent Array Center	sopac.ucsd.edu	GAMIT
IGG-VLBI	Institut für Geodäsie und Geoinformation, Bonn		Calc/Solve

Tab. 1b: Stations used in this study

Station	EPN		JPL		SOPAC	
	time span	quality	time span	quality	time span	quality
BRUS	11,5	high	13,4	high	14,0	high
DELF	10,1	medium	3,7	medium	-	-
DENT	10,4	high	-	-	-	-
DOUR	11,0	high	-	high	-	-
EUSK	9,3	medium	-	-	-	-
GRAZ	15,0	very high	14,7	very high	15,8	very high
HERS	15,9	low	15,6	low	16,6	medium
HFLK	11,5	medium	11,3	medium	-	-
KARL	9,2	high	-	-	-	-
KLOP	8,2	high	-	-	-	-
KOSG	16,0	high	15,7	high	16,3	high
OBER	-	-	-	-	4,6	high
ONSA	11,5	high	15,5	high	16,1	high
POTS	11,5	very high	11,9	very high	13,5	very high
PTBB	7,7	high	6,2	high	-	-
TITZ	-	-	4,6	medium	-	-
WARN	4,2	medium	3,1	medium	3,1	medium
WSRT	10,4	very high	10,1	very high	10,8	very high
WTZR	11,5	high	11,7	high	12,3	high
ZIMM	11,5	medium	12,7	medium	15,2	medium

With this material we will try several different approaches to provide additional information about the accuracy of the site velocities. We consider comparisons between results from different independent analyses, the temporal evolution of results at the centers as data accumulate and software systems are improved, and use the results from different receivers at one site. To start with, we need to take a closer look at problems related to the application of the stochastic models commonly used in the GPS analyses.

3.1 Formal errors

Generally, station coordinates and velocities (rates of change of coordinates) are computed simultaneously in so-called global solutions together with their respective variances and covariances (e.g. Nikolaidis 2002). In the case where site velocities are derived directly from the time series of daily (or weekly) coordinate solutions, the velocity errors come as a by-product from the least squares model fits to the data. Because in this process the data covariance information is not propagated, it has to be reproduced empirically from the time series itself. Neglecting the correlation between data points by setting cov(τ) = 0 would mean to stipulate the domination of white noise. In this case, for a series of N equidistant data points in time the root variance (σ_v) of the rate in a two-parameter linear fit becomes (Zhang et al. 1997):

$$\sigma_v = \frac{\sigma_r}{T}\sqrt{\frac{12T/\Delta t}{(1+T/\Delta t)(2+T/\Delta t)}} \qquad (1)$$

with T length of the series in years, Δt data interval and σ_r the error of a daily coordinate solution. In order to account for the effect of grossly underestimating the actual error level, the σ_v - values may just be scaled by an empirical factor which can be determined e.g. from test campaigns. In **Fig. 2** have we used a scale factor of 3.0 to be applied to the typical white noise error value of ±3.0 mm of a single day GPS horizontal position determination. In this representation of the basic error law for time series of length T(y) = N/365 we have included the actual errors from the EPN (CLEAN) time series analysis downloaded in 4/2008 for a subset of 38 stations. Those stations closest to the line of the upscaled error law represent the 'best behaved', while those further away from the ideal error line are more strongly affected by anomalous signals, a situation that can be readily verified by examining the corresponding time series plots.

Facing the systematic effects seen in the majority of the time series, analysis groups have developed more refined stochastic models based on covariance input derived from spectral analysis of the series (Zhang et al. 1997, Nikolaidis 2002, Williams 2003). This leads indeed to more realistic error estimates, although the determination of parameters for the different types of noise remains rather uncertain (Mao et al. 1999).

3.2 Power law noise

Spectral analysis is a useful tool for analysing the noise features typically seen in most of the time series (Agnew 1992). On the basis of a generalised power law of the form $P = P_0 (f/f_0)^{\kappa}$ with f as sampling frequency and P_0 and f_0 scaling coefficients, three types of noise can be defined, characterized by values of 0, -1 and –2 of the exponent κ, which stand for white noise, flicker noise and random walk, respectively. Introducing covariance information estimated from the power specra (Zhang et al. 1997), the formal errors obtained in the fit increase with growing values of κ, which is easily appreciated knowing that data correlation reduces the redundancy of a least squares solution. To first approximation and for n equidistant data points the rate errors are proportional to $1/n\sqrt{n}$ for white noise, 1/n for flicker noise and $1/\sqrt{n}$ for random walk.

A comparison of the velocity errors from three different analysis centers in the histograms in **Fig. 3a,b** shows the effect of applying different stochastic models: the JPL Flinn Analysis apparently uses a white noise model while EPN and SOPAC use coloured noise models.

As an example of spectral analysis, we show the power spectrum of the JPL time series of station Wettzell (WTZR), displaying the annual peak as well as peaks at higher frequencies such as the fortnightly tidal oscillation of 13.66 d, the latter indicating a deficiency in the tidal model of the analysis software **(Fig. 4)**.

Here we like to point out that the high frequency oscillations are of little or no effect on the rate estimates of longer series, quite in contrast to the detrimental effect of the lower order harmonics (Blewitt and Lavallee 2002). To document this, in a special low order Fourier analysis we chose the base frequency $\omega_0 = 2\pi/T_0$ with T_0 = 20yr for 10-yr time series **(Fig. 5a,b)** obviating the large energy in the low period range from 1 to 20 years. As an example, we choose the BRUS North component of the 13,4 yr JPL data set after velocity estimation showing the detrended residuals (Fig. 5a). The presence of long period signals is obvious and could be related to a low frequency type of oscillation. The nature of periodic or quasi-periodic signals beyond the ubiquitous annual oscillation still remains elusive. It could just be the result of changes in the equipment and/or analysis approach. Other sources could be found in anomalous hydrological cycles (e.g. groundwater variations) or monument instability. If groups of stations suffer similar variarions one should consider the impact of higher order ionospheric terms (Steigenberger et al. 2006). Irrespective of the origin of the longer period variations one can apply the rules discussed by Blewitt and Lavallée (2002) to estimate the velocity bias resulting from the unmodelled oscillation. Thus, in the case of a 10-yr 'wave' with an amplitude of 2.5 mm one would obtain a maximum bias of 0.5 mm/yr if the data span T matches the length of the period, i.e. 10 yrs, but the bias would quickly fall to zero for T = 15 years, oscillating around decreasing values from 0.25 mm/yr downwards for longer T (scaling Fig.3 in Blewitt and Lavallée).

3.3 Problems with individual stations

The assessment of the quality of fit of the time series of the individual analysis centers is made easy by the steadily improved content and layout of the websites (Tab.1). Moreover, it is possible to download the data and apply one's own models and software to reproduce and check the results (Section 3.2).

Going through the time series plots offered by the different websites, we found several aberrant results, most of which were corrected in the ensuing updates. Here, we like to show just one example which is typical for any one of the analysis centers and a consequence of the enormous amount of data that has to be routinely treated in global networks. In the SOPAC analysis of the station Kootwijk (KOSG) the data of the GIG campaign in 1991 and the data in early 1992 caused difficulties in the fitting model that led to velocity estimates off by more than 1 mm/yr. The problem could be easily identified in the de-trended residual plots **(Fig. 6)** and was subsequently corrected by excluding the data from 1991 to 1992.3. This, however, was the only correction actually applied, in order to safeguard the authenticity of the data drawn from external sources.

3.4 Temporal evolution of velocity estimates

To evaluate the accuracy of the velocity solutions, it is instructive to look at the effects of improving data quality, software upgrades, such as new and better models for atmospheric delays, antenna calibration on the results as they evolve. Here we like to present as an example several different downloads from the JPL FLINN Analysis Center that occurred during our work in the period 2000 to 2008 **(Fig 7a,b)**. From our list (Tab. 1) we selected seven stations in central Europe with best performance in terms of length of series and quality of velocity fit.

The salient features in the behaviour of the seven selected stations are common shifts related to changes in the reference frame realised in the different solutions. For studies on crustal deformation in regional and local networks these changes are of little or no effect. The important aspect here is the change in the *relative* behaviour of the velocity values among the stations. The trend observed in Fig. 7a,b is evident: most velocity values run in parallel and show relative variations smaller than 0.3 mm/yr. To better quantify our conclusion, we formed differences between pairs of stations to eliminate the frame effect and calculated a WRMS from differences between the two latest download dates of 2007.4 and 2008.3 **(Tab. 2a,b)**.

Tab. 2a,b: Evolution of velocity results of the JPL analyses. DD = Double differences for the two latest download dates T_1 and T_2. The resulting WRMS for the North and East components are: $wrms_{North} = \pm 0.101$ and $wrms_{East} = \pm 0.113$ mm/yr. σ_{T1} and σ_{T2} are the white noise rate errors from the respective JPL analyses

a)

North comp.	T_1 = 2007,4 mm/yr	T_2 = 2008,3 mm/yr	DD mm/yr	σ_{T1} mm/yr	σ_{T2} mm/yr
POTS - WTZR	-0,38	-0,29	-0,09	0,022	0,022
ONSA - ZIMM	-1,45	-1,55	0,1	0,042	0,028
KOSG - BRUS	0,95	1,03	-0,08	0,022	0,022
HERS - KOSG	-0,06	0,25	-0,31	0,036	0,036
BRUS - WTZR	-0,19	-0,19	0	0,022	0,022

b)

East comp.	T_1 = 2007,4 mm/yr	T_2 = 2008,3 mm/yr	DD mm/yr	σ_{T1} mm/yr	σ_{T2} mm/yr
POTS - WTZR	-1,14	-1,15	0,01	0,036	0,036
ONSA - ZIMM	-2,58	-2,93	0,35	0,050	0,042
KOSG - BRUS	0,61	0,46	0,15	0,028	0,028
HERS - KOSG	-1,28	-1,34	0,06	0,054	0,045
BRUS - WTZR	-2,83	-2,83	0	0,036	0,036

From this example we conclude that one-sigma velocity errors cannot presently be considered to be smaller than 0.1 mm/yr for the best stations. Of course, larger variations are seen in the first sections between 2000 and 2003, in compliance with the fact that the time series were still rather short (4 to 6 years) in the early phase of permanent observations.

3.5 Different receivers/antennas at one site

Operating different systems at one site has proven to be a very efficient way of establishing realistic accuracy estimates. Within the IGS network the Geodetic Observatory of Wettzell offers the possibility to compare velocity results from five different receiver/antenna assemblies deployed on a platform of the observing tower of the main building **(**Söhne et al. 2005, **Fig. 8a)**. The data from all five of these receivers are being routinely processed and made publicly available at the JPL Flinn analysis center (ref. see Tab.1). In spite of the small sample size, we believe that the comparison does provide useful complementary information for the present accuracy discussion.

The errors that can be brought to light by comparisons at one single site are mainly due to the instrumentation and include antenna calibration problems, receiver malfunctions or other deficiencies. If we focus on the velocity determination and not so much on the coordinates themselves, it is the *change* in any of the system parameters that is essential. One can imagine changes in the antenna setup, the mount and the environment as being most harmful to site velocity determinations.

In **Fig. 8b** we plotted the velocity vectors for the five receiver/antenna assemblies with reference to the weighted mean of the individual values in order to illustrate the spread of the results. If the formal errors (see section 3.1) were correct, statistically two of three vectors (65%) should vary within a circle of only 0.1 mm radius. The actual spread reflects above all the effect of observing time, i.e. different length of the series. Stations with series of less than 5 years suffer from anomalous deviations of more than 1 mm/yr (Blewitt and Lavallee 2002). In **Tab. 3a,b** we compiled the RMS errors for the north, east and up components, showing that a standard time series of 10 years duration would realistically produce RMS errors of about 0.3 mm/yr in the horizontal components.

Tab. 3a: JPL results for the five antenna/receiver sets at Wettzell

antenna/receiver	obs. time period	v_{North}	σ_{vNorth}	v_{East}	σ_{vEast}
	y	mm/yr	mm/yr	mm/yr	mm/yr
WTZJ	4,5	14,28	0,06	20,44	0,09
WTZZ	4,5	15,36	0,07	18,98	0,11
WTZT	6,0	15,43	0,06	20,54	0,09
WTZA	6,1	15,36	0,04	20,12	0,05
WTZR	11,7	15,37	0,02	20,33	0,03

Tab. 3b: Wettzell antenna/receiver velocity accuracies. The errors are calculated from the JPL velocity estimates shown in Tab. 3a.

	WRMS (of one individual antenna/receiver) mm/yr	σ (weighted mean velocity of 5 antennas) mm/yr
North vel.	0,28	0,14
East vel.	0,30	0,15
Up vel.	0,73	0,26

3.6 Comparison between solutions from different GPS analysis groups and centers

In the comparisons, we have narrowed our focus on the West-central part of Europe and plotted the vectors in a magnified scale in order to be able to identify any obvious streams of velocities **(Figs 9a,b,c).** The global reference frames of the JPL and SOPAC velocity data were rotated to the Eurasia-fixed frame using the absolute plate rotation values of the ITRF2005 given by Altamimi et al. 2007. In order to facilitate the visual comparison between solutions, we had to apply a small additional rigid rotation to the SOPAC data set. For the purpose of this study, i.e. comparing only deformations or *relative* site motions, the actual amount of rotation is irrelevant. Moreover, more sophisticated approaches using adjustments on a selected set of 'stable' sites would require a significantly larger set of points (Scherneck et al. 2002 , Nocquet and Calais 2003).

In all three representations (EPN, JPL and SOPAC), the E-W pattern of motions remains rather accidental and does not suggest any significant E-W-extension above the level of about 0.3 mm/yr. In contrast to this we see a rather persistent north-eastward trend of the sites in the northern Alps and their foreland. In southern Sweden, the site of Onsala, whose motion is also well documented in the SWEPOS and BIFROST campaigns, shows a sustained south-western trend. This motion is in good agreement with GIA models (Scherneck et al. 2002). The stations in central Germany (WTZR, POTS, HOBU, PTBB) all have rather small residual N-S components. The sites west of the Rhenish rift system in Belgium, the Netherlands and southern Britain (HERS) tend to show somewhat larger individual motions although they are located fairly closely together. In this context we should like to emphasise that we have to refrain from any deeper discussion of the vector fields of motion, because they are highly dependent on the choice of a 'crust fixed' reference frame. Nocquet and Calais (2003) went through great pains to define a stable 'no motion' reference in central Europe using all available stations and had to accept a remaining level of residual motion of 0.5 mm/yr. It is of interest to note that even at this early stage (data from 1996-2001) the coherent N-E motion of the three pre-Alpine sites ZIMM, HFLK, GRAZ and the N-S convergence is just about to manifest itself (their Fig. 3).

To arrive at quantitative measures that can be used in further comparisons, we computed mean velocity gradients from linear fits in E-W and N-S profiles, or rather profile swaths for the available stations in each one of the analyses **(Figs 10a,b,c)**, in a way similar to e.g. Mourabit et al. (2008). The deformation trends are quite consistent in all three of the solutions (Tab. 4) and support the visual impression from the vector plots in Figs. 10-13, i.e. that the E-W extension is all but marginally recognisable, while the N-S compression appears quite clearly with a mean value over 1000 km of 1.2 ± 0.15 mm/yr.

Tab. 4: Average strain rates in N – S and E – W profiles. The gradient units are equivalent to strain rate in nanostrain/yr, i.e. 10^{-9} /yr. n = number of stations in each data set. Mean = weighted mean of all three data sets with n used as weight.

Data Source	N-S velocity gradient (mm/yr)/1000km	n	E-W velocity gradient (mm/yr)/1000km	n
EPN - GPS	-1.423 ± 0.14	12	-0.335 ± 0.27	16
JPL - GPS	-1.109 ± 0.11	9	0.416 ± 0.31	9
SOPAC-GPS	-0.907 ± 0.12	6	0.465 ± 0.11	6
Mean	-1.204 ± 0.15		0.038 ± 0.27	

3.7 Comparison with VLBI measurements

As far as independent techniques such as SLR and VLBI are concerned, the small size of the area under study undoubtedly precludes any useful comparisons with the GPS results. In the frame of the regular European VLBI sessions, however, there is a possibility to look at a three station configuration which covers the central part of western Europe, i.e. the triangle formed by the stations of Onsala, Wettzell and Effelsberg **(Fig. 11).** The Effelsberg 100m radio telescope is located just west of the Rhenish Embayment in the northern foothills of the Eifel-Ardennes Massif. Although heavily burdened by astronomical observations, regular time windows have been set aside for geodesy to permit a meaningful contribution to the global and European geodetic VLBI programs. The long time series in combination with the low level of long period systematic effects makes the VLBI results particularly suitable and valuable for the present study.

In particular, the time series for the length of the baseline Effelsberg – Wettzell **(Fig. 12)**, which crosses the Rhenish rift zone, gives an indication of the VBI data rate and quality and leaves little room for any E-W- extensional motion beyond the level of 0.3 mm/yr (in terms of integrated relative motion over 500 km). From the vectors in Fig. 10 we can derive the same conclusion for the E-W-direction, i.e. $dv_{E-W} \leq 0.3$ mm/yr. Conversely, we do see part of the N-S compression observed by GPS, i.e. about 1 mm/yr.

4. Conclusions

The overall picture gleaned from the comparisons may be interpreted as a consequence of the presence of a N-S-compressional regime due to the alpine thrust in the South and the horizontal component of the GIA in the North. We found signs of an N-S velocity gradient of 1.2 mm / 1000km = 1.2 nanostrain per year, or in other words a compressional deformation at a level of 1 to 2 mm/yr between southern Scandinavia and the northern Alps and their forelands. This observed trend is inherent in both the GPS analyses as well as in the VLBI results. Furthermore, we can confirm earlier research on the absence of any detectable E-W extensional motion (Nocquet and Calais 2003), and lower the limit of significance to a value of ≤ 0.3 mm/yr. This is an important result in view of the seismo-tectonic risk assessment in the area of the Cenozoic Rift System (Camelbeek and Meghraoui 1996). However, to guard against any misconceptions about the interpretation of the observed discrete site motions we emphasise that the results stated here represent *integral* relative motions over large distances and should not be compared directly with locally derived motions on fault systems.

The group of stations in the north-west of central Europe shows several larger particular motions that do not seem to fit with any general tectonic trends. This behaviour forms a distinct contrast to the stations further east, which have been showing a rather stable relationship for many years now.

The small number of sites involved in this study still asks for caution before any firm conclusions can be drawn, in particular considering the unknown influence of long period effects discussed in section 3.2. Therefore, the inclusion of more permanent stations in the crustal deformation studies is urgently needed. In this respect, the German GREF network will be of great benefit (Ihde et al. 2005), much like the French Regal network and others to be used in combinations for creating denser fields of points for high resolution velocity determination (Dong et al. 1998, Nocquet and Calais 2003, Camelbeek et al. 2008).

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Fig. 9a: EPN velocity vectors for central-western European stations; shaded lines indicate the limits of the E-W and N-S profiles

Fig 9b: JPL velocity vectors; shaded lines indicate the limits of the E-W and N-S profiles

Fig. 9c: SOPAC velocity vectors; shaded lines indicate the limits of the E-W and N-S profiles

Fig 11: IGG-VLBI velocity vectors

Fig.1: Overview of the Cenozoic Rift System showing main tectonic features and seismic activity (from GEO, No.1, January 1984) *Rheinisches Schiefergebirge:Rhenish Massif, Kölner Bucht: Lower Rhine Embayment, Französisches/Südwestdeutsches Schichtstufenland:*
Figure caption: Earthquake epicenters 1000-1983, with magnitudes M, mining induced shock, quake with major damage

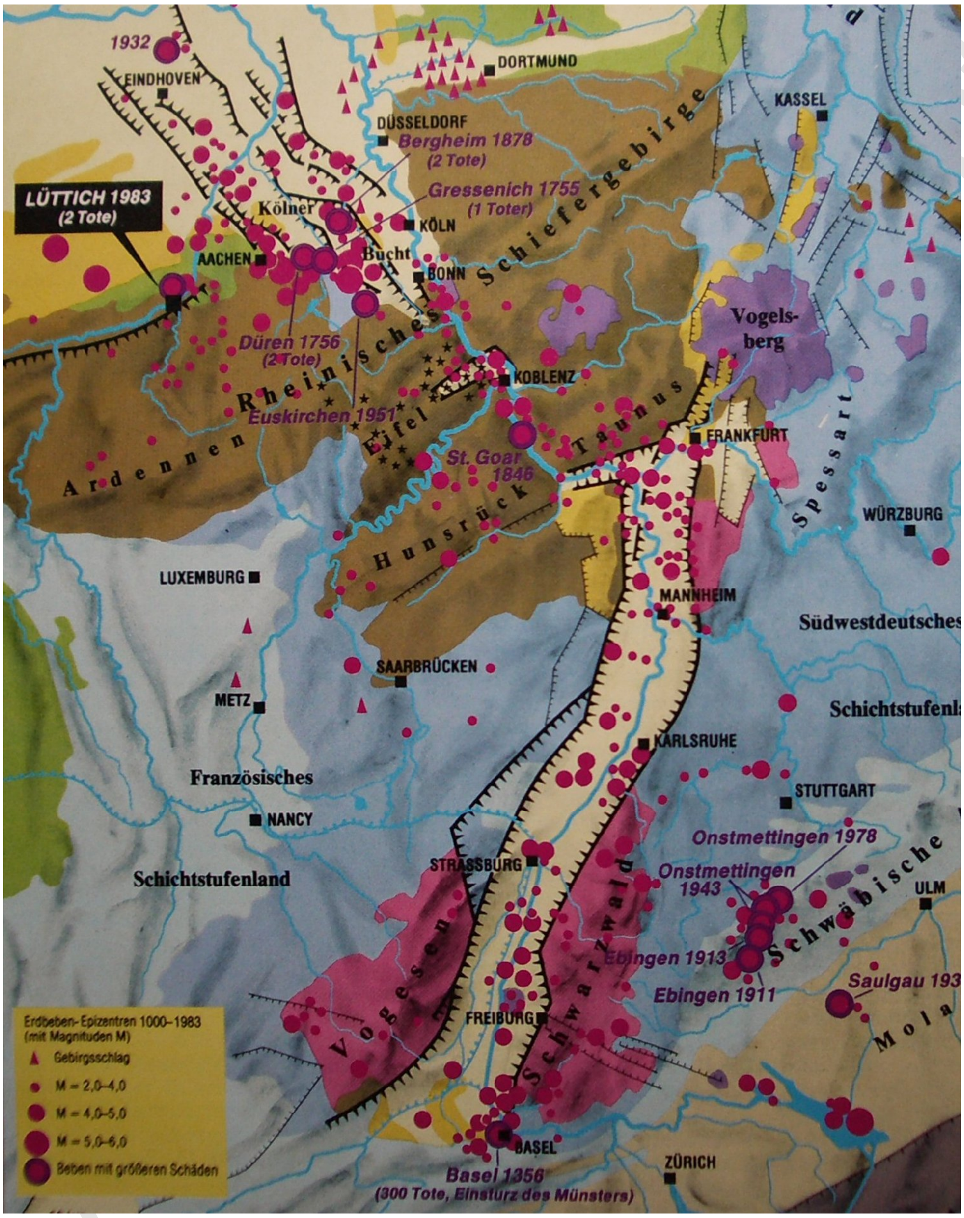


Fig 2: Time series error law for white noise (enhanced by an empirical factor 3) for comparison with errors given in the EPN CLEAN velocity results.

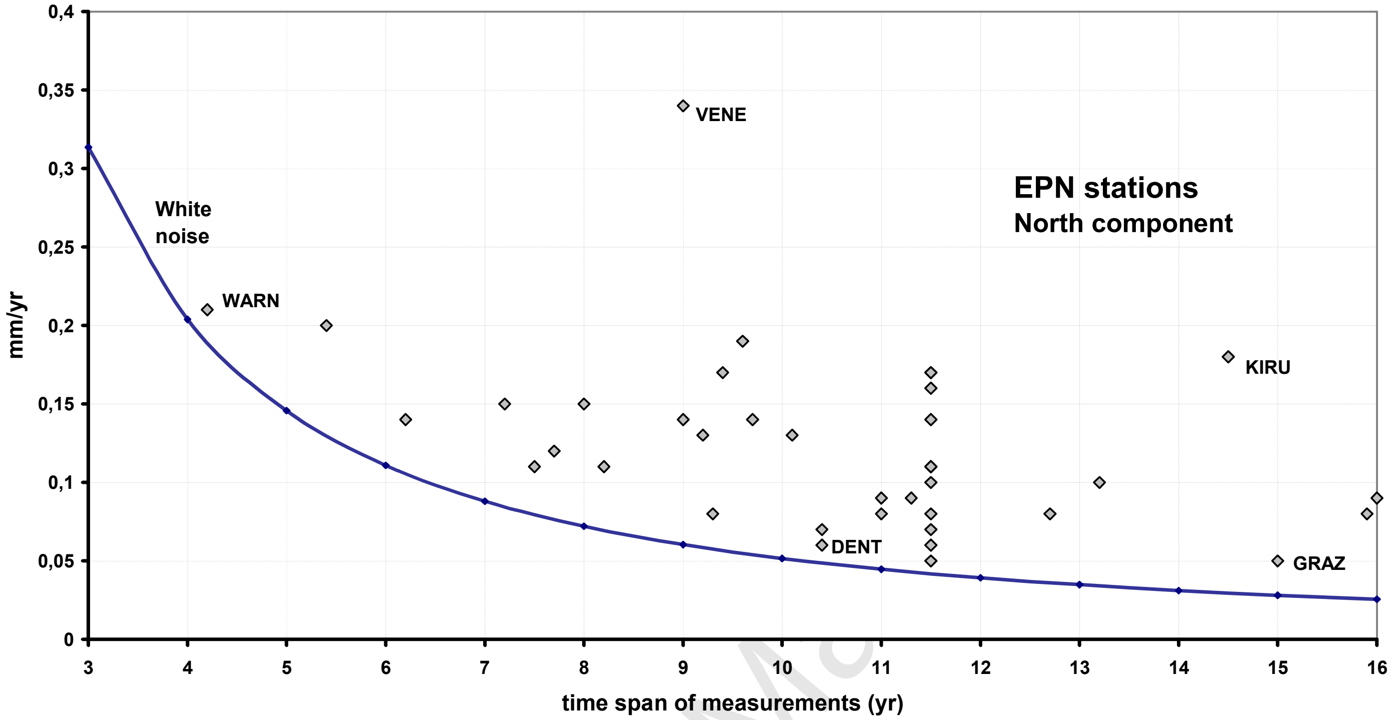
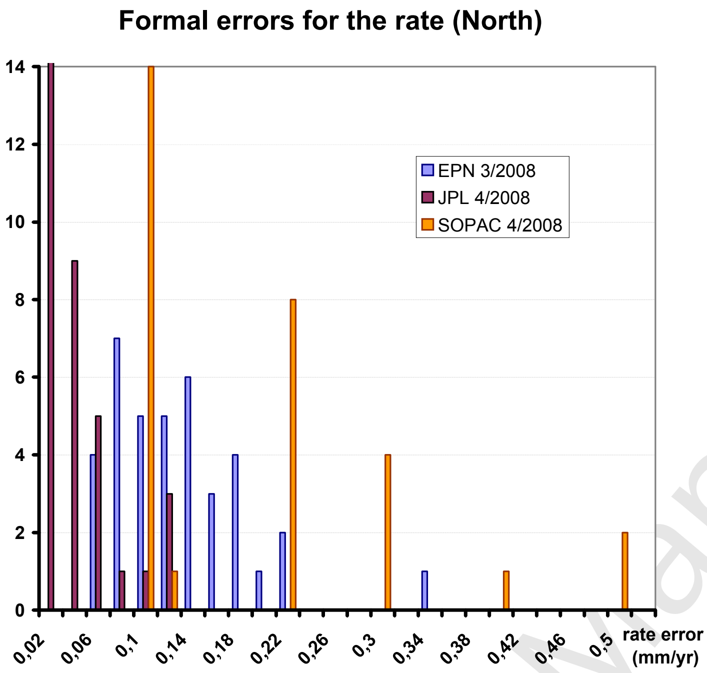


Fig. 3a,b: Histograms for the formal velocity errors of the 2008 EPN, JPL and SOPAC solutions



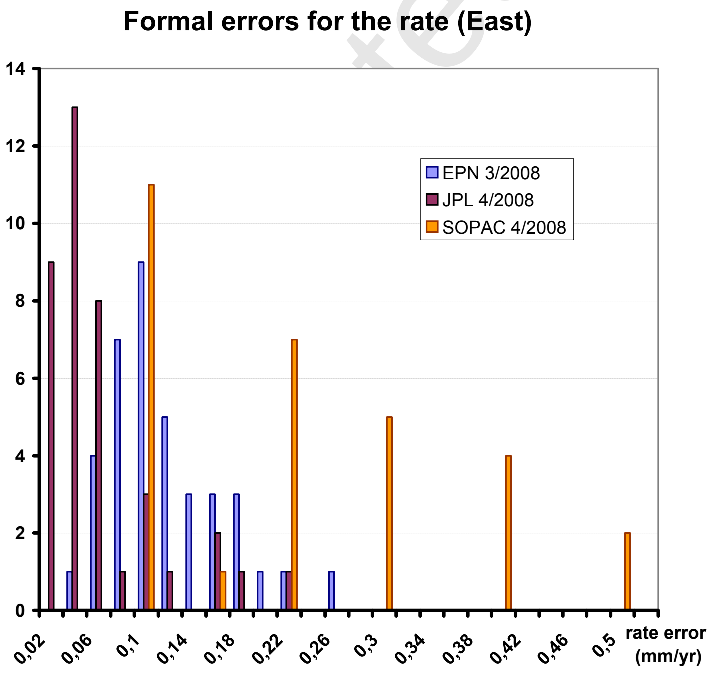


Fig 4: Power spectrum of the JPL time series for the Wettzell North component (detrended) showing considerable energy in the low frequency part.

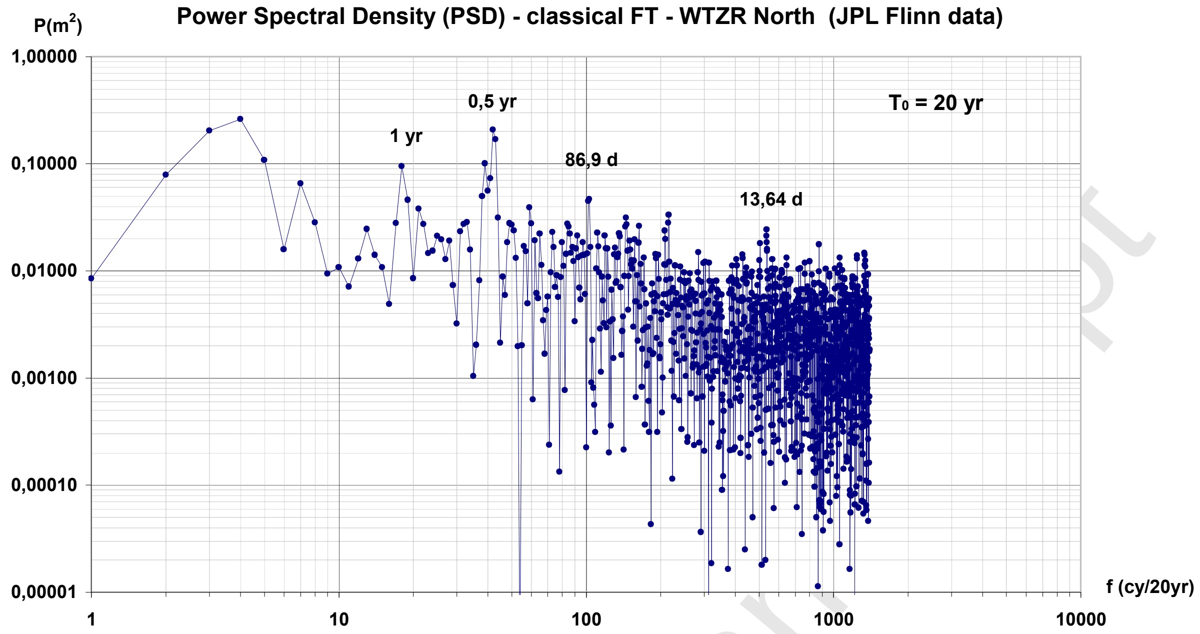


Fig. 5a: BRUS North component after elimination of linear trend (v_N). The presence of long period oscillations is clearly visible in the temporal behaviour of the residuals.

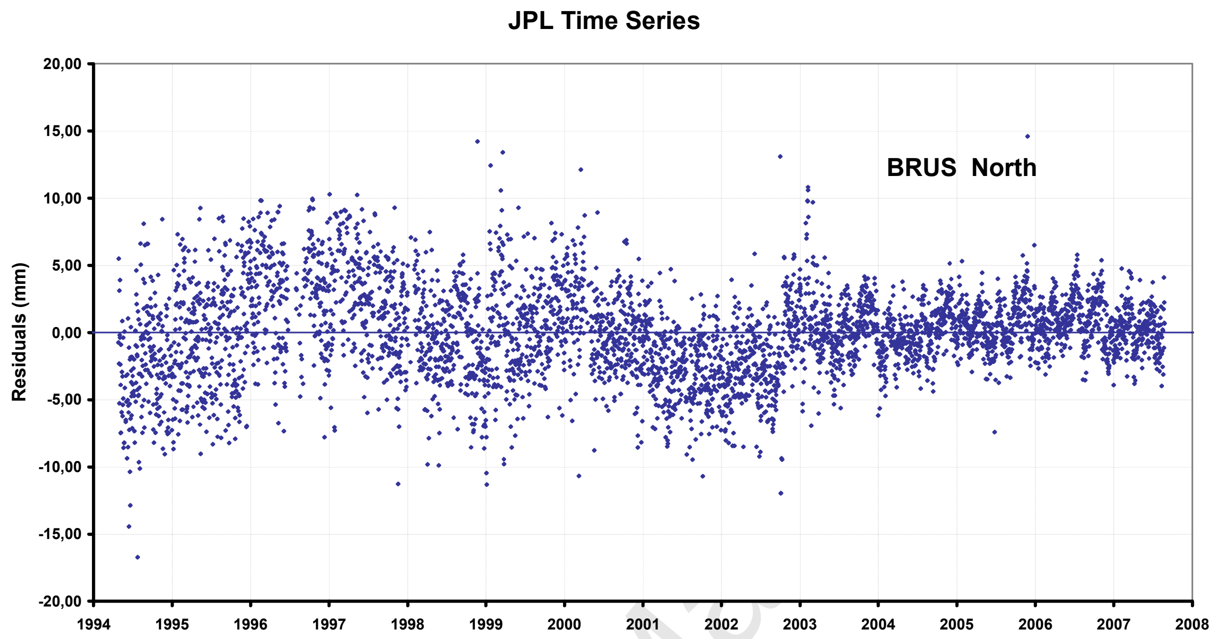


Fig. 5b: Low order spectral power contained in the time series of the residuals in Fig. 5a with maxima at periods of 1,0 (annual period) 3,2 and 10 years.

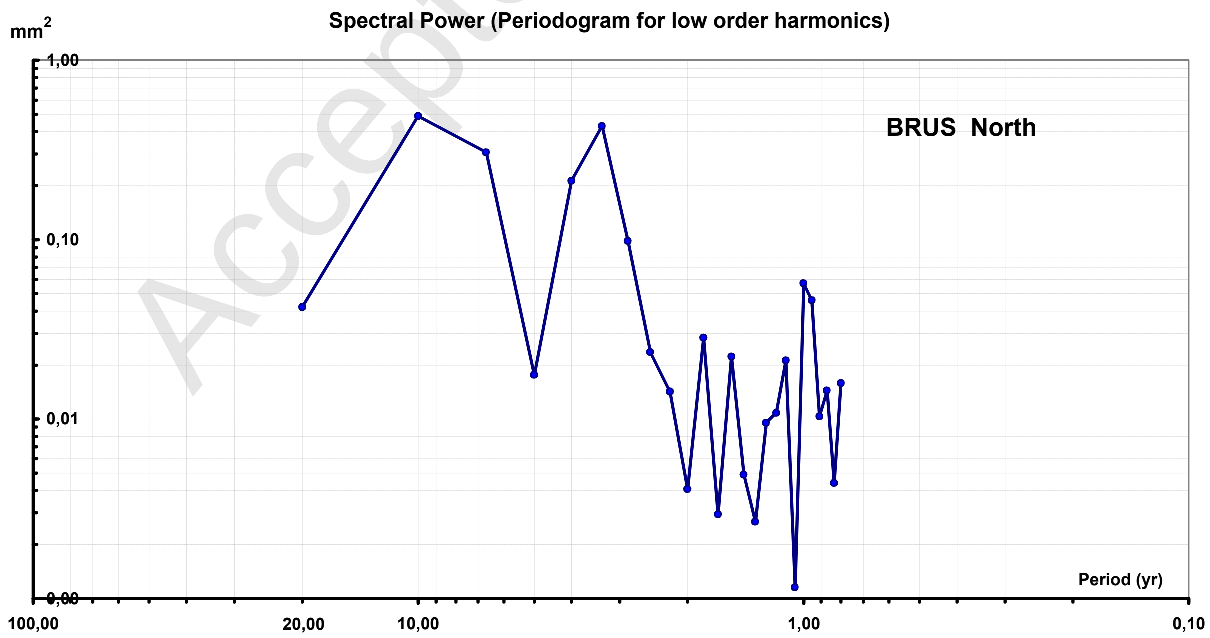


Fig. 6: Problems with SOPAC solution for station Kootwijk (KOSG). The early data in 1991 (GIG campaign) are probably the reason for the misfit. The fitting model for the rate includes annual and semi-annual components, which appear to be of transient nature in this example and hence cannot be properly accounted for (Nikolaidis 2002).

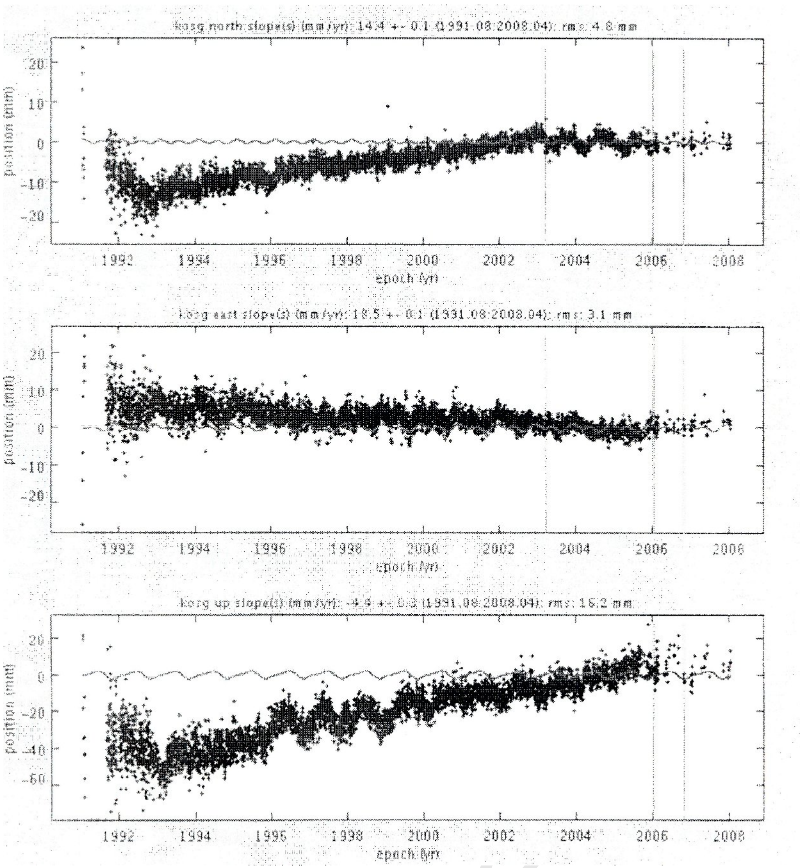


Fig 7a: Temporal evolution of velocity solutions: East component

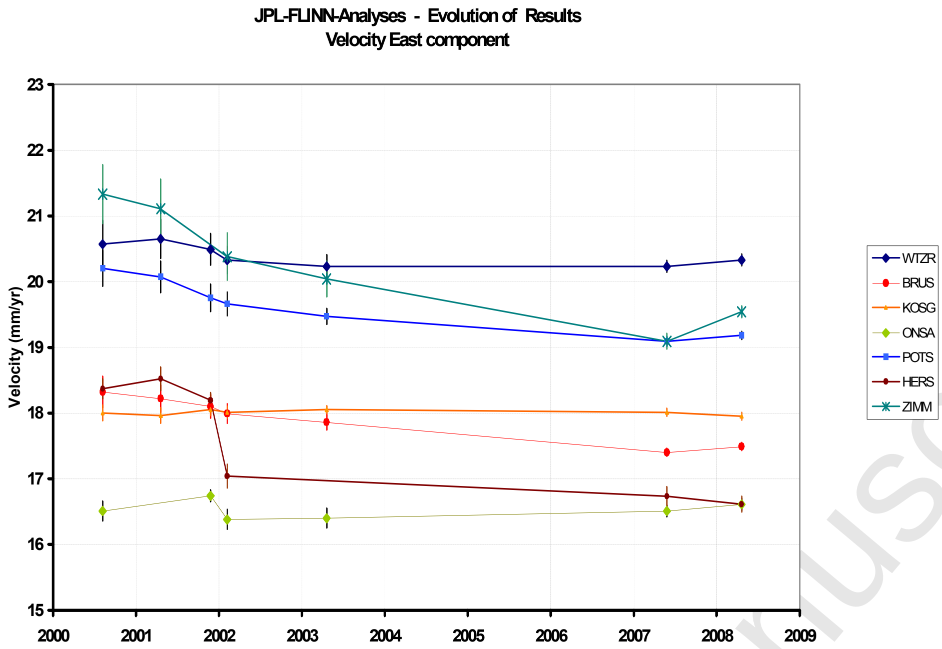


Fig 7b: Temporal evolution of velocity solutions: North component

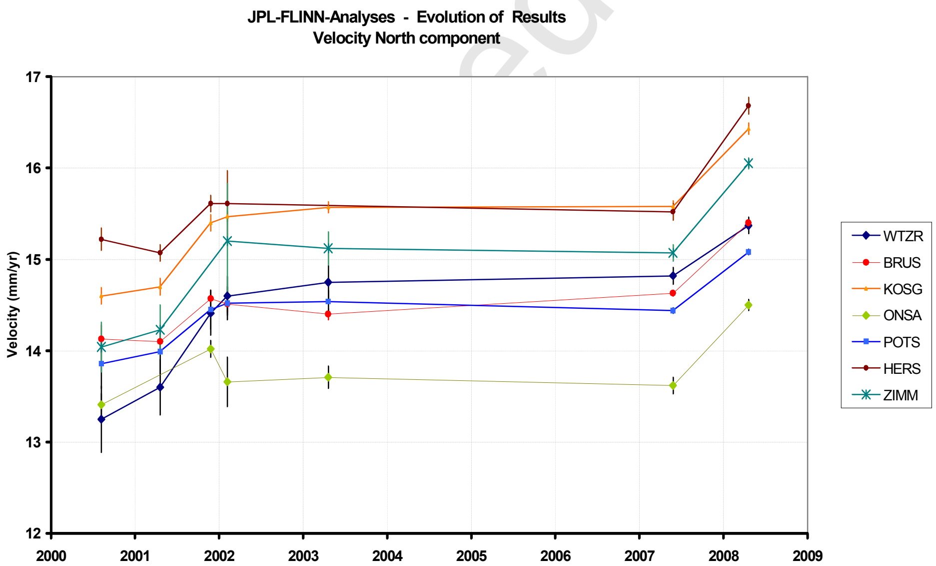
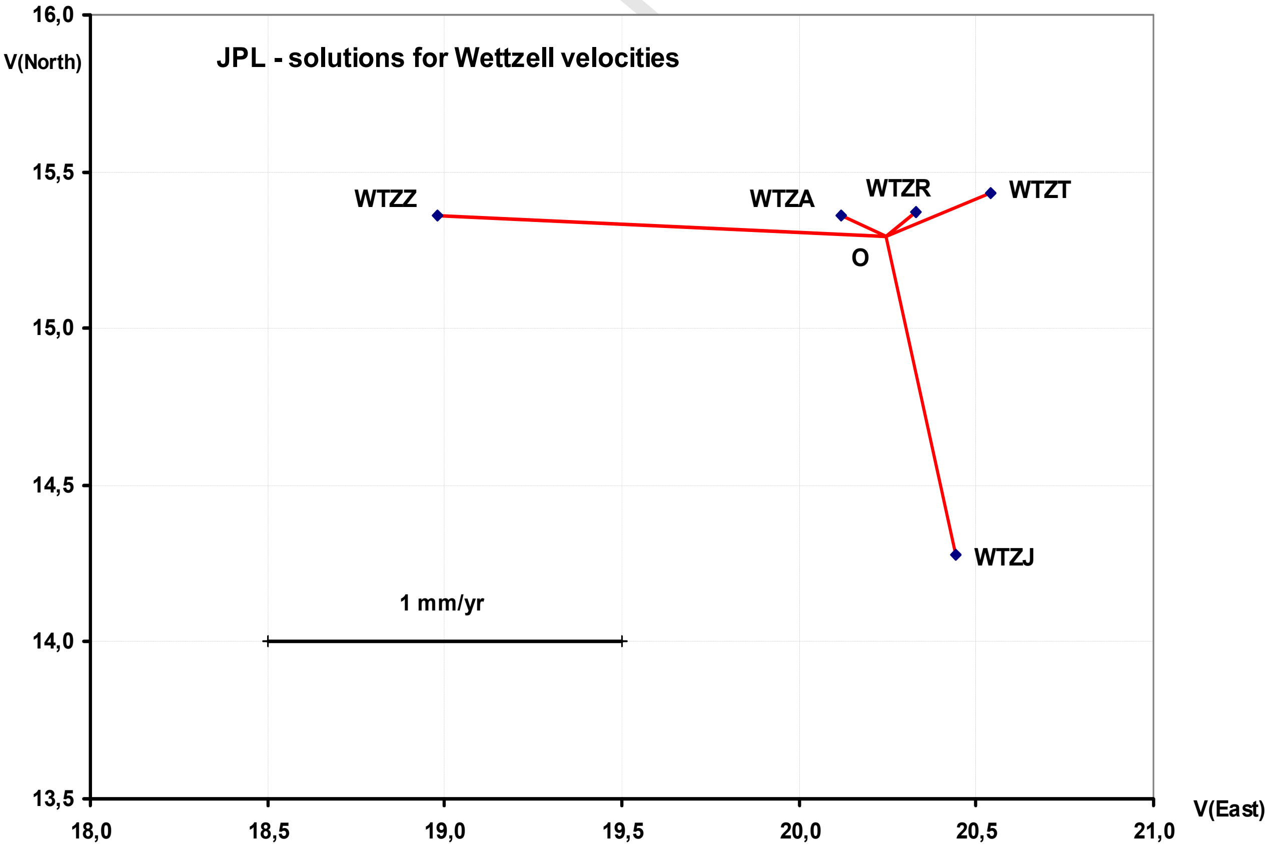
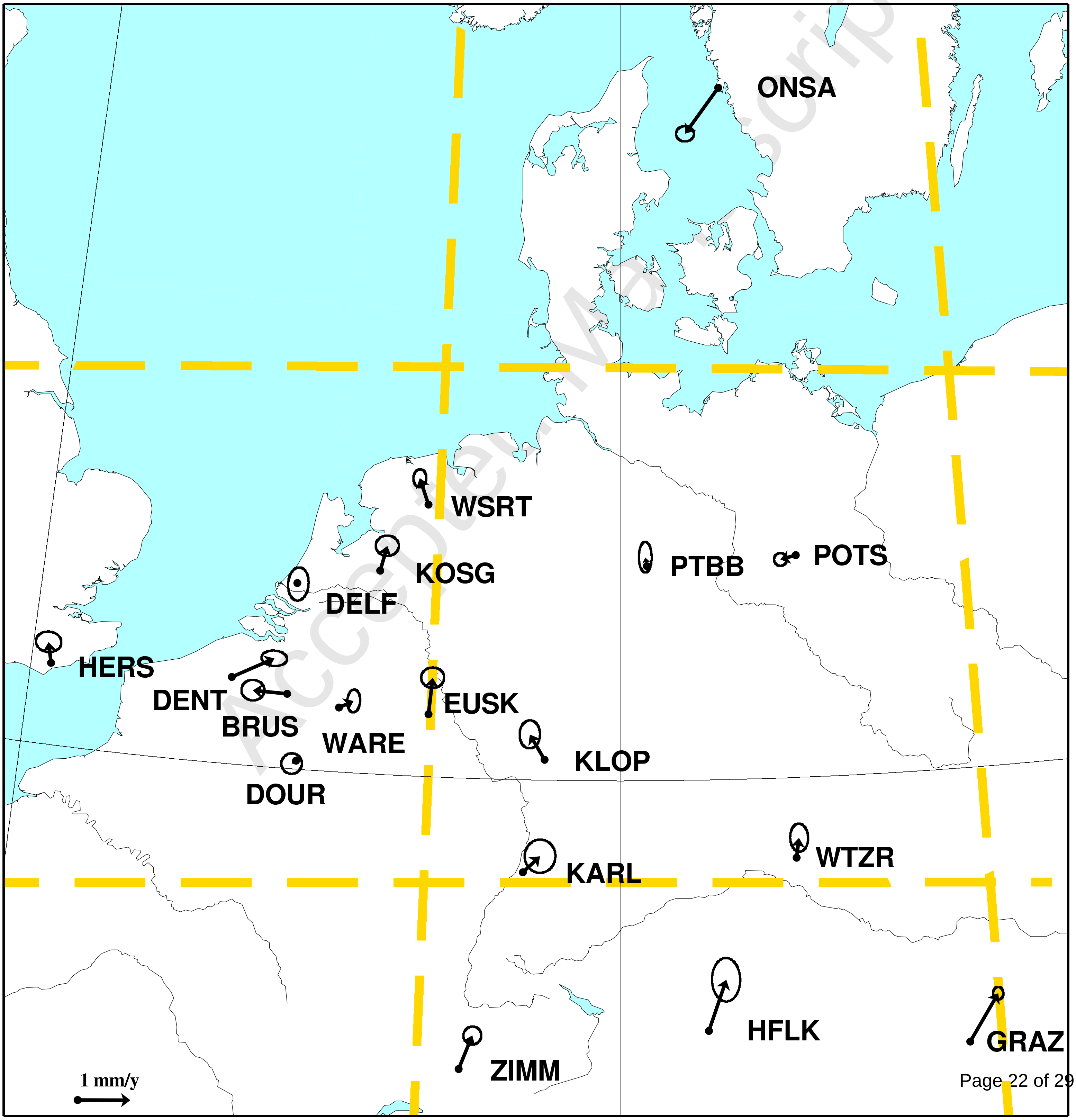


Fig 8a: Wettzell 5-antenna platform

Fig. 8b: Velocity results from JPL analysis for the five antenna/receiver units operating permanently at the Fundamental Station of Wettzell.




ONSA
WSRT
PTBB
POTS
KOSG
DELF
HERS
DENT
BRUS
WARE
EUSK
KLOP
DOUR
KARL
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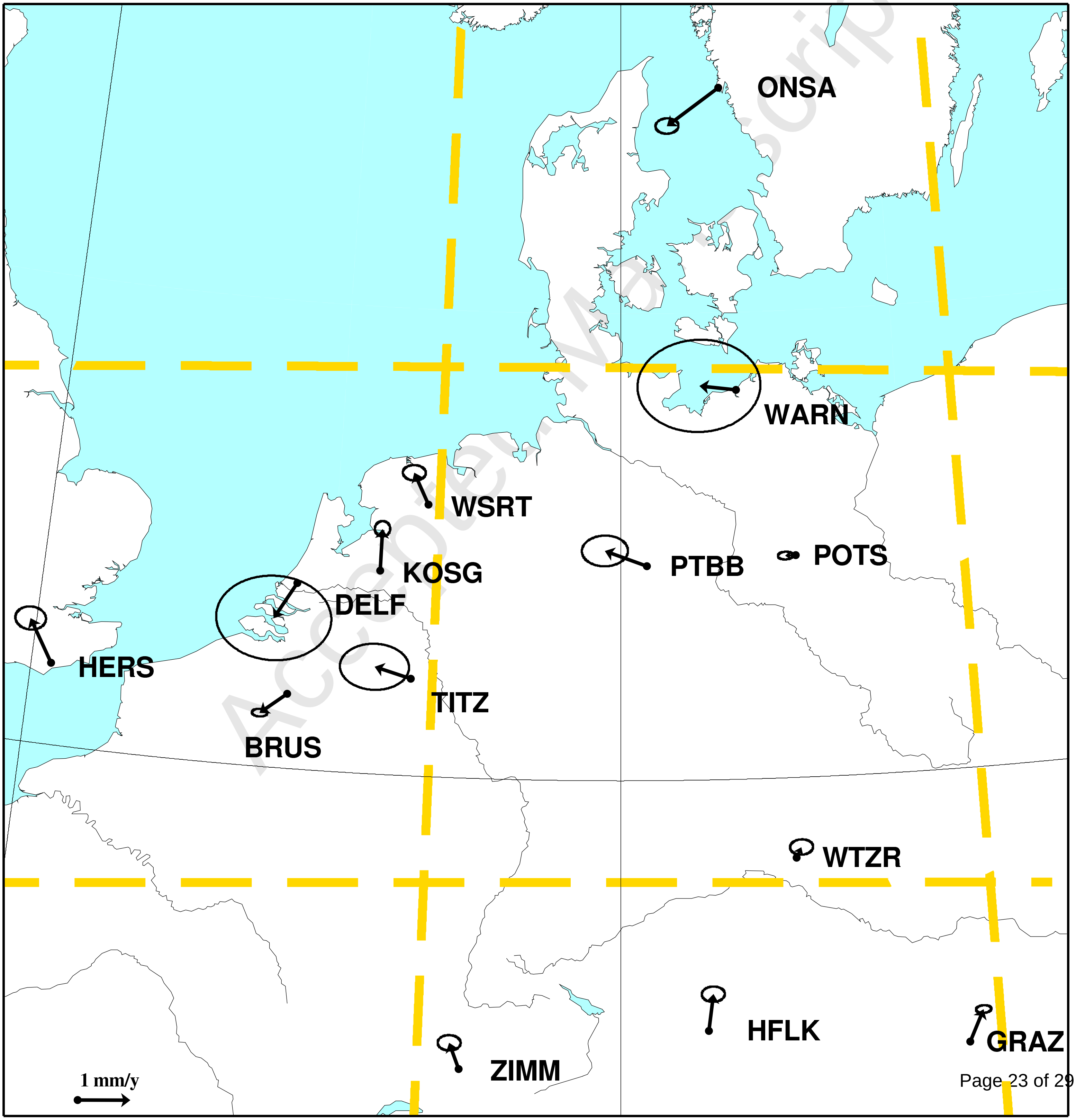
GRAZ
ZIMM
1 mm/y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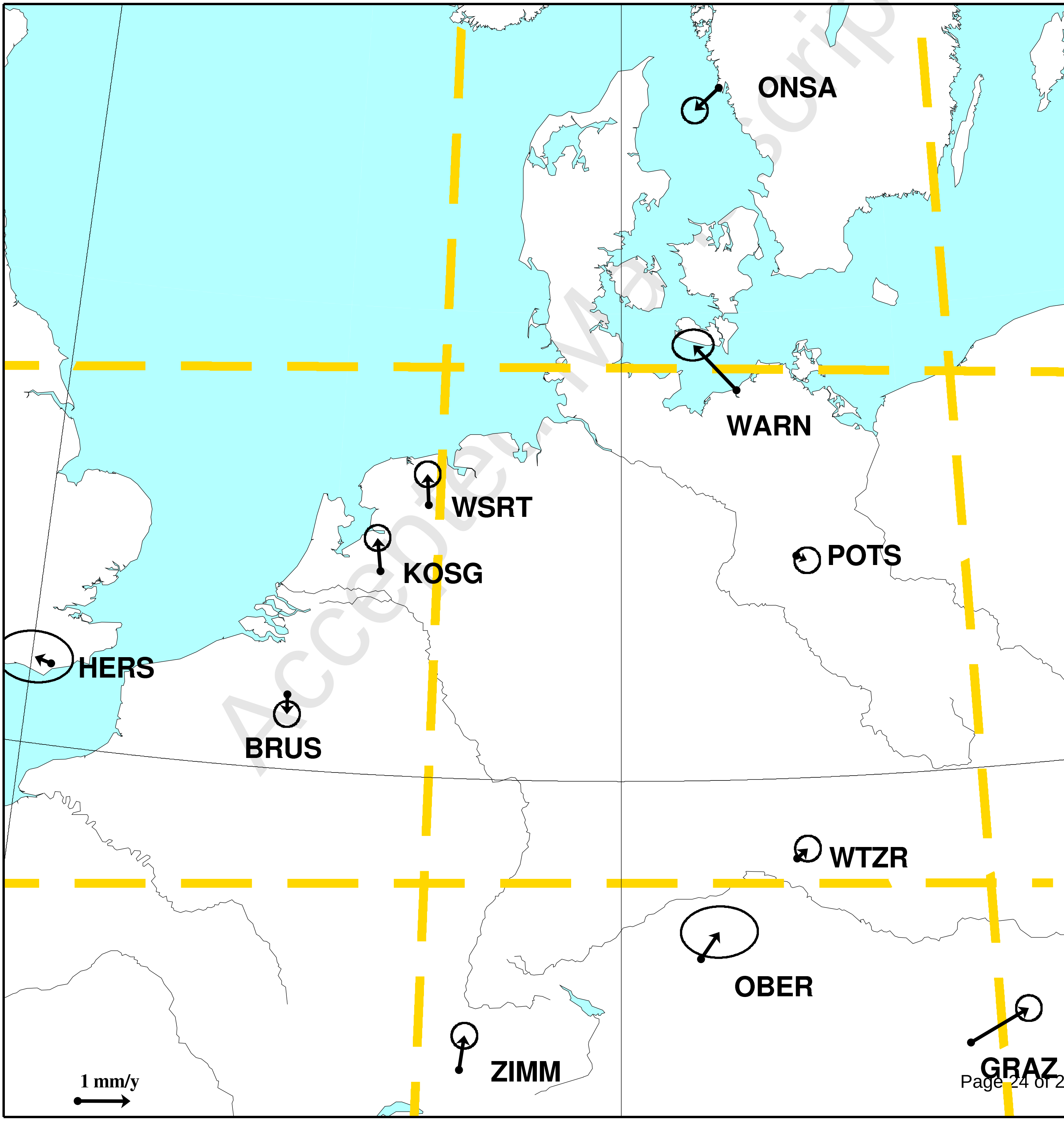
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Fig. 10a: N-S profile and E-W profile velocity gradients from EPN data

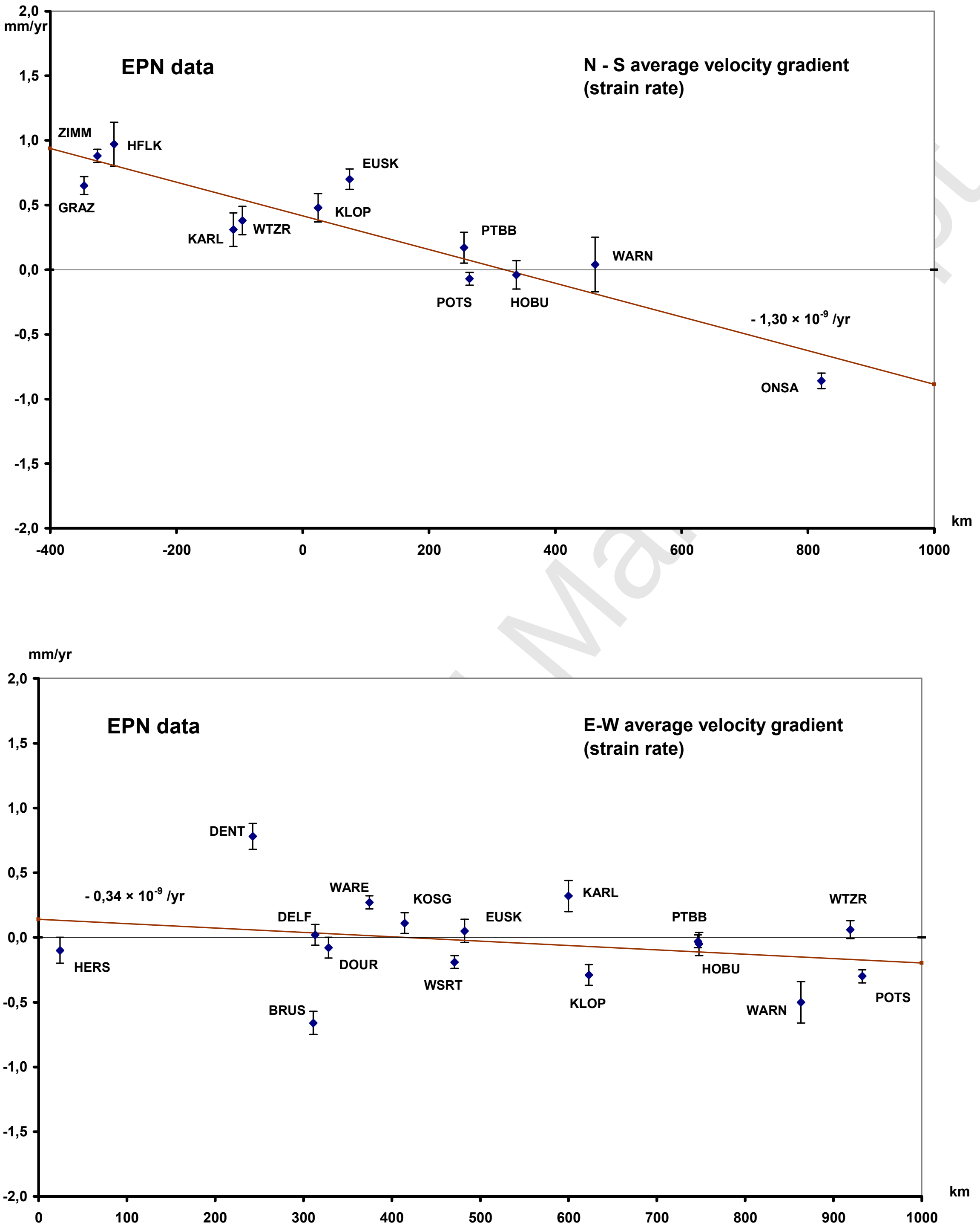
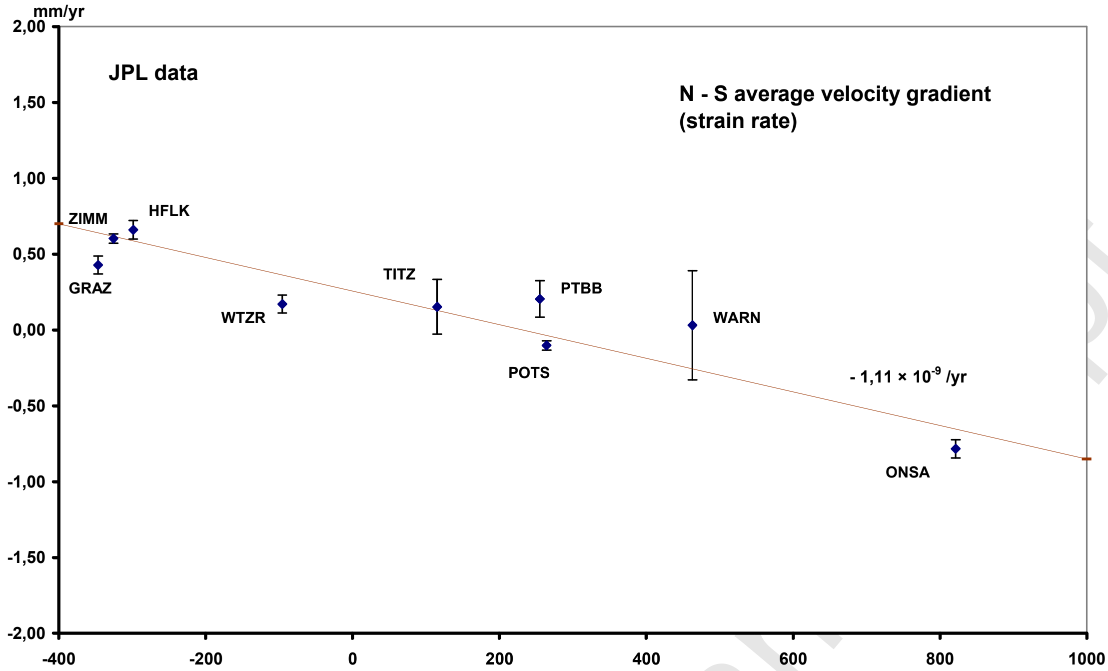


Fig 10b: JPL N-S and E-W mean velocity gradients



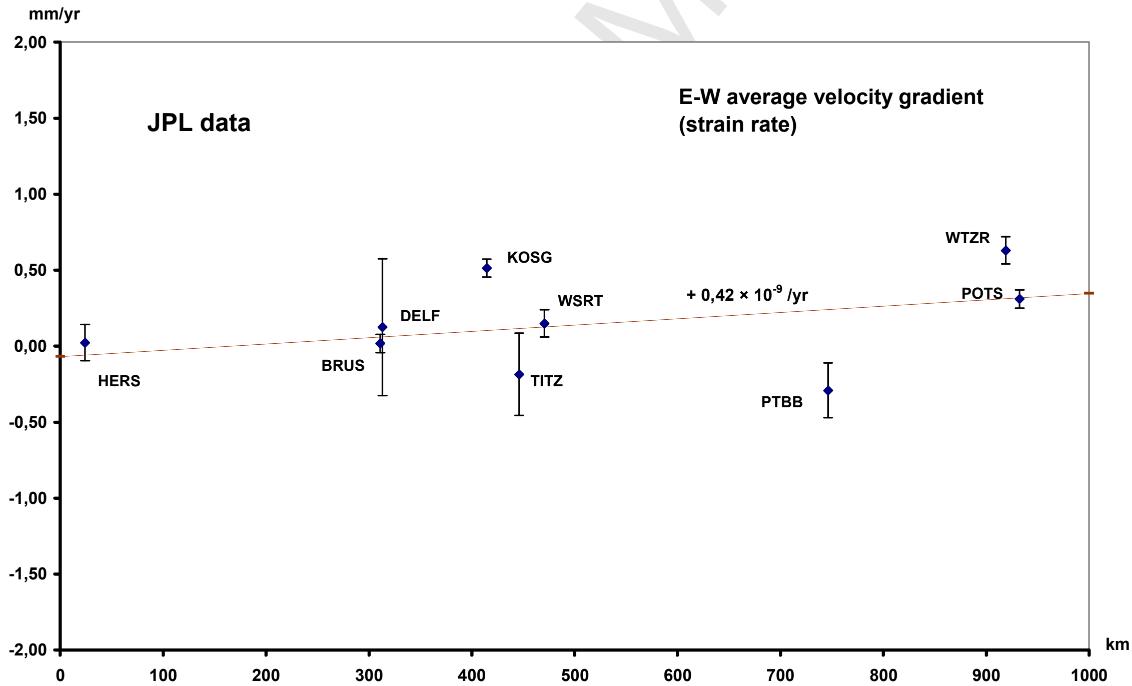
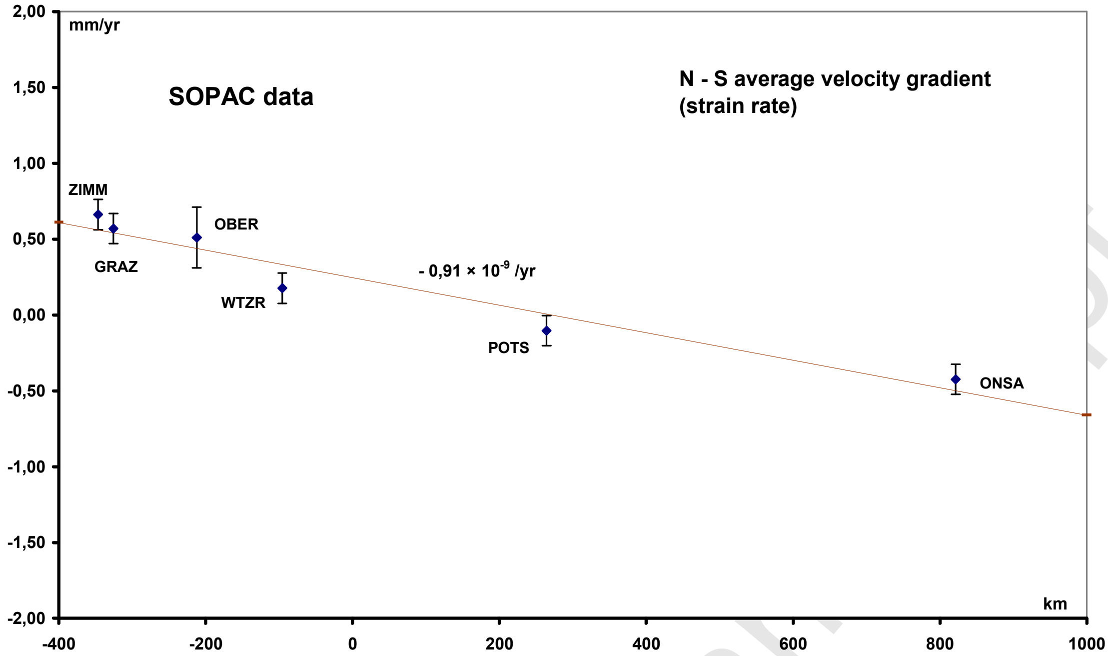
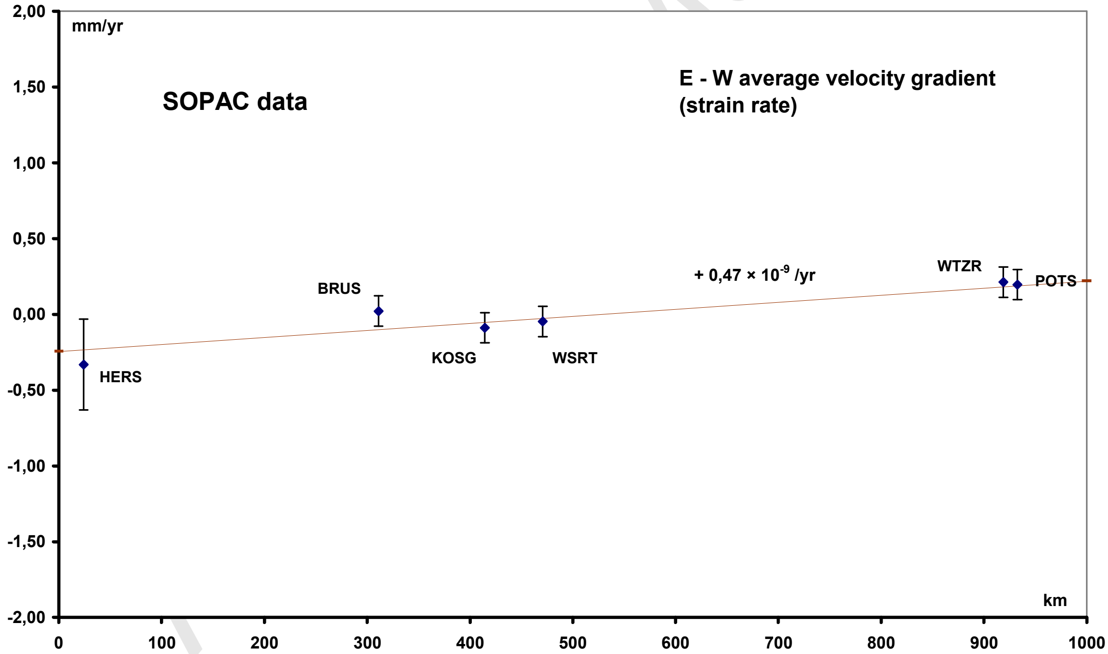


Fig. 10c: SOPAC N-S and E-W mean velocity gradients






Onsala
Effelsberg
Wettzell
1 mm/y

Fig. 12: VLBI baseline lengths, Effelsberg – Wettzell, slope = -0.086 ± 0.12 mm/y