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GPS monitoring of vertical ground motion in northern Ardenne–Eifel: five campaigns (1999–2003) of the HARD project

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Abstract We present the HARD project of GPS monitoring of vertical ground motion in NE Ardenne and Eifel (western Europe). Its main purposes are to get a better insight into the present-day rates of vertical ground motion in intraplate settings and to identify the various causes of these motions. Since 1999, we have carried out yearly campaigns of simultaneous GPS measurements at 12 sites situated so as to sample the different tectonic subunits of the study area and especially to record potential displacements across the seismogenic Hockai fault zone. Five campaigns (1999–2003) have been processed currently. Key issues of the data processing with the Gamit software are discussed and first results are presented. Though temporally consistent in many cases, the obtained vertical motion rates are spatially highly variable. They are also much too high (several mm/year) to support a tectonic interpretation, and a long-term influence of groundwater level variations is proposed to account for the observed motions. This influence should be distinguished from seasonal variations and from inter-survey variations linked to the varying degree of soil and subsoil drying off during the successive spring surveys.

Keywords GPS · Vertical crustal motion · Water loading · Ardenne · Eifel · Rhenish shield

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Introduction

The knowledge of the spatial and temporal characteristics of present-day uplift and subsidence of ancient massifs is very helpful not only in understanding the geodynamics of intraplate areas, but also in assessing the seismic hazard in these regions of weak to moderate seismicity. However, as a matter of fact, in many cases uplift rates deduced from geodetic data are higher than geological rates by one order of magnitude (Table 1), making their tectonic interpretation often doubtful. Until recently, most data on present-day vertical ground motion were provided by levelling comparisons. However, though highly precise, the levelling technique suffers from several shortcomings. Systematic measurement errors are often difficult to detect (Stein 1981). Instability of the geodetic monuments alters the measured ground movements (Wyatt 1989). Various near-surface causes of motion (atmospheric and water loading, soil swelling and shrinking, compaction, human activity) interfere with a possible tectonic component. In brief, the signal-to-noise ratio of levelling data is very low in intraplate areas, requiring that two conditions be fulfilled in order to obtain reliable information on vertical motion trends. Firstly, long-term records (> 10 years) are needed to overcome measurement noise. Secondly, frequent remeasurements are highly desirable in order to separate a long-term trend of a few 0.1 mm/year from seasonal and inter-annual variations with a cm-scale amplitude (Demoulin and Collignon 2002).Yet, the acquisition of

Table 1 Geodetic versus geological rates of vertical ground motion in intraplate settings

Area	Geodetic, mm/year	Geological (1-0 Ma), mm/year	References
Regional motion			
Eifel (D)	1.6	0.25	Mälzer et al. 1983 ↔ Meyer and Stets 1998
S Limburg (NL)	0.8	0.06	Kooi et al. 1998 ↔ van den Berg 1994
Upper Rhine graben (F)	> 1.0		Liaghat et al. 1998
W Brittany (F)	1.0	~0.1	Lenôtre et al. 1999 ↔ Hallegouet and Van Vliet 1986
NE Spain (SP)	0.8		Gimenez et al. 1996
Ardenne (B)	1.3	~0.1	Pissart and Lambot 1989 ↔ Demoulin 1995
Fault motion			
Roer graben (NL)	1.5	0.07–0.1	van den Berg 1994 ↔ Meghraoui et al. 2000
Upper Rhine graben (CH)		0.2	Meghraoui et al. 2001
E Betics (SP)	0.9–2.0	0.08–0.15	Gimenez et al. 2000 ↔ Silva et al. 2003

levelling data for larger areas is time-expensive; hence, too few surveys are generally available for assessing confidently the vertical motion trend.

The GPS is a valuable alternate solution for monitoring vertical displacements. Although it presents similar flaws (numerous error sources, monument instability, near-surface causes of motion) and it is less precise than levelling for short baselines (< 20 km), it has the great advantage that frequent measurements may be carried out more easily. Ideally, continuous monitoring can be provided by a network of permanent GPS stations (Calais et al.2001). However, proceeding by campaigns still requires a long period of time (≥10 years) to get reliable estimates of vertical movement rates. First encouraging results have already been obtained from a decade of measurements in the Lower Rhine Embayment and the northern Eifel (Görres and Campbell 1998), and several GPS networks recently started recording vertical ground motion in various parts of intraplate NW Europe, like e.g. the EUCOR URGENT network in the Upper Rhine Graben (Rozsa et al. 2003).

Launched in 1999, succeeding 10 years of high-precision levelling (Demoulin and Collignon 2000, 2002), the HARD (Höhenänderungen in den ARDennen) project monitors vertical ground motions in an area of northern Ardenne and NW Eifel centred on the presumably uplifting Hautes Fagnes high (Fig. 1). Five yearly campaigns of GPS measurements have so far been carried out in the early spring periods of 1999–2003. The project aims to answer the following main questions. Is the NE Ardenne massif currently uplifting with respect to its foreland, and, if so, at which rate? Is there any differential motion between subareas of the massif (e.g. between the Malmédy graben and the Hautes Fagnes and Weisser Stein highs)? Does any displacement take place along the seismogenic Hockai fault zone? In its first part, this paper describes the HARD network configuration and the methodology adopted. Then, we present the results of the first five campaigns, with preliminary velocity estimates. Finally, we discuss the quality of the GPS solutions, the meaning of the obtained velocities and the appropriateness of the GPS sites for further measurements.

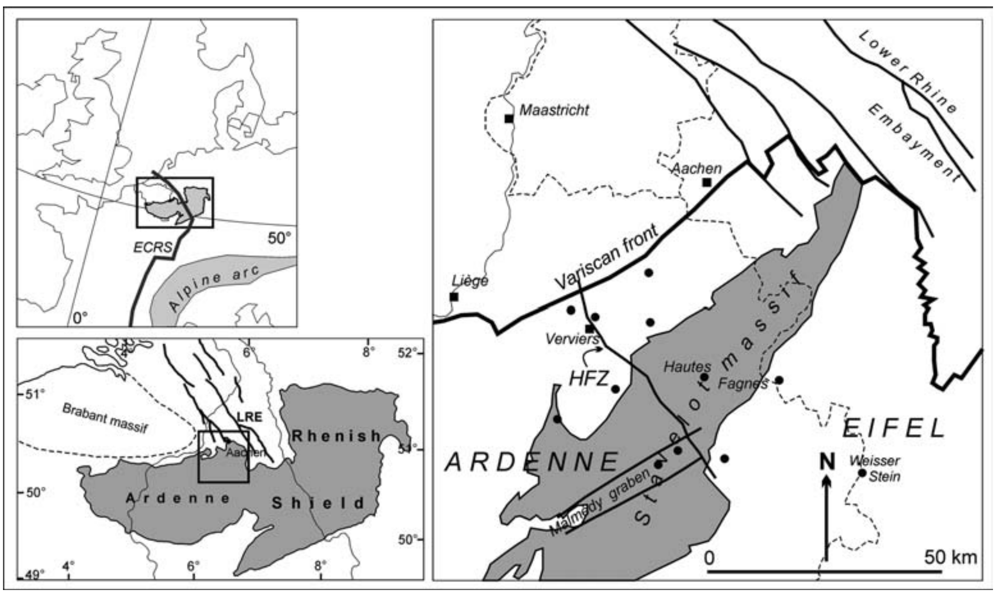


Fig. 1 Geological sketch map of the study area. In the large-scale map, solid circles denote the HARD sites. The Variscan front marks the northern border of the Paleozoic Ardenne massif and the Cambrian Stavelot massif appears in *grey*. Hockai fault zone (HFZ) . Lower Rhine Embayment (LRE). European Cenozoic rift system (ECRS)

Neotectonic setting of the study area

The study area is located in the NE part of the Ardenne and in the NW Eifel, in the western half of the Rhenish shield, which is situated in the foreland of the Alpine orogen and straddles the active West European Cenozoic rift system (ECRS) (Fig. 1, 2). The HARD network is centred on the Hautes Fagnes massif and extends across its NE margin, ~20 km southwards of the major bounding faults of the Lower Rhine graben. Not far away from the Variscan front, the Hautes Fagnes area corresponds to the northern half of the Cambrian Stavelot massif, where the Variscan fold-and-thrust belt has superposed on structures inherited from the Caledonian orogeny, resulting in a structurally complex basement wherein longitudinal ENE–WSW folds and thrust faults are cut by numerous NW–SE to NNW–SSE striking normal faults.

The region has uplifted between 400 m and 500 m since the Oligocene, chiefly in response to far-field stresses. The uplift rate sharply increased from the Pliocene, culminating at 0.1 mm/year in the mean in the early and middle Pleistocene. Studies of Quaternary river incision suggest that a maximum uplift of 200–250 m could have occurred in the Eifel and NE Ardenne during the last 800 kyears (Meyer and Stets 1998). However, river downcutting strongly decreased or even ceased since 400 ka (Quinif 1998; Van Balen et al. 2000), suggesting that uplift rates up to ~0.5 mm/year could be reached in that part of the massif between 800 ka and 400 ka but that tectonic quiescence prevailed in recent times. Several causes are invoked to explain the middle Pleistocene uplift pulse, which could result from the combined influence of intraplate compression, mantle upwelling and rift shoulder uplift (Van Balen et al. 2000; Garcia-Castellanos et al. 2000).

Superimposed on this epeirogenic upheaval, several NNW–SSE normal faults cutting the Stavelot massif and its northern foreland have been reactivated in close relation with the opening of the Lower Rhine rift segment since the upper Oligocene. At least one of them, the Hockai fault zone, has a marked morphological expression in the Verviers area (Fig. 1, 2) and has recorded instrumental seismicity during the last 20 years. More generally, the Lower Rhine graben and its western shoulder, including the NE Ardenne, are currently characterized by weak to moderate seismicity (Ahorner 1983). One of the most violent historical earthquakes having ever struck NW Europe, the Verviers earthquake, in the year 1692, occurred in, or very close to, our study area (Camelbeeck et al. 1999).

A number of studies used levelling data to estimate present-day rates of vertical motion in the Ardenne–Eifel and its surroundings. Jones (1950) published data of the Belgian IGN suggesting that the Hautes Fagnes massif had uplifted at a rate of 1–2 mm/year between 1892 and 1948. According to a questionable interpretation by Pissart and Lambot (1989), the same area would then have subsided by ~40 mm from 1948 to 1976. However, Mälzer et al. (1983) calculated a maximum uplift rate of 1.6 mm/year for the nearby western Eifel during the same period. Moreover, whereas the velocity estimates for the Ardenne relate to a reference point located at Uccle (Brussels), outside the massif, the western Eifel is thought to move up with respect to reference points located within the Rhenish shield. In the nearby Maastricht area, Kooi et al. (1998) consider that the tectonic component of the recorded uplift is in the order of 0.5–1 mm/year.

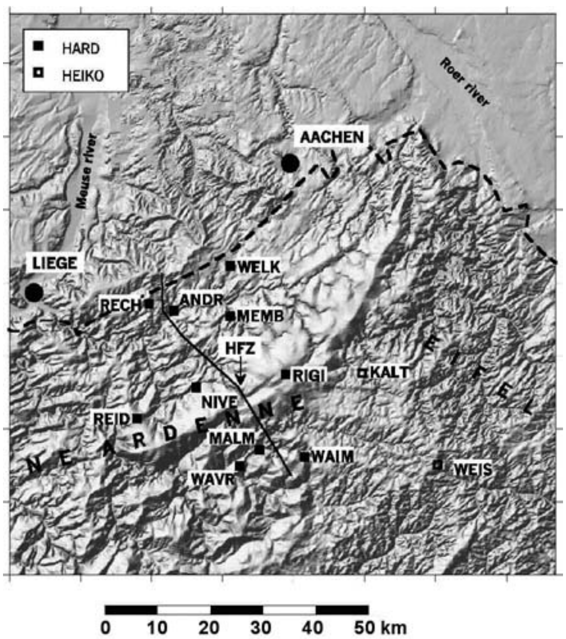


Fig. 2 Location of the HARD GPS sites (+ two additional HEIKO sites) on a DEM of NE Ardenne and Eifel. The *dashed line* marks the contact between the Rhenish shield to the south and respectively the Mesozoic Pays de Herve to the NW and the Cenozoic Lower Rhine Embayment, part of the ECRS, to the NE. HFZ. Hockai fault zone

Methodology

The results presented in this paper have been obtained by campaign-style GPS measurements over a time period of 4 years (1999–2003). Due to the very small rate of the tracked motions, our observing and data processing strategies have to be extremely sophisticated.

Data acquisition

Our GPS network has been designed to cover the three main subunits of the study area, i.e. the Hautes Fagnes massif, its northern foreland to the north of the Variscan front and the Malmédy graben to the south (Fig. 1, 2). Within the massif, the GPS sites are arranged to record the differential behaviour of the Baraque Michel and

Weisser Stein highs (RIGI and WEIS in Fig. 2) and the intervening high-plateau area. This design also yields three transects across the Hockai fault zone, one in each tectonic subunit. The baseline lengths range between 3 km and 44 km with an average of 19.9 km. The maximum difference in height between the sites is 438 m. At the HARD GPS sites, the antenna supports have been anchored in the roof's concrete cornice of flat-topped buildings more than 20 years old, so that problems of monument instability are minimized and visibility is excellent down to 10° elevation at least. Moreover, we use the permanent GPS station of the Royal Observatory of Belgium at Membach and two sites of the HEIKO project in western Eifel (Görres and Campbell 1998; Campbell et al. 2002).

Epochwise, the annual measurement campaigns are always carried out in the same season, i.e. the early spring. At each campaign, all sites are occupied simultaneously during at least 72 h, yielding three or more 24-h sessions. Although we were not able to use GPS equipment of the same manufacturer and type over the whole network, the same antenna/receiver pairs always reoccupied the same sites so that the network's instrumental configuration is identical from one year to the other.

Data processing

We have processed the data with the Gamit/Globk 10.07 software (King and Bock 1998; Herring 1999), which uses double differences of the phase and code data on the ionosphere-free L_c combination to compute a network solution in a two-step approach in session mode (Feigl et al.1993). Moreover, an independent analysis using the Bernese GPS software satisfactorily checked the presented results (Mesenholl 2003).

We used the IGS precise orbit sp3 files, from which we estimated orbital initial conditions. We ensured that, based on this estimation, the general postfit rms on the orbit parameters did not exceed 0.05 m. This was imposed by the time window covered by the 24-h-sessions, generally running from 06.00 UTC to 06.00 UTC and therefore implying to model the satellite orbits from two sp3 files for a 48-h time interval. This might induce a degradation in the quality of the orbit modelling (King R, written communication), so that it was required occasionally to remove one or two badly behaving satellites (generally with at least one orbit parameter rms >0.5 m). We also included in the calculated network five IGS permanent GPS stations (BRUS, GRAS, HERS, KOSG, WTZR) which encircle and enlarge the HARD network, therefore expecting to reduce the impact of external error sources on the intra-HARD baselines. Moreover, their well-constrained coordinates and velocities allow us to stabilize the solutions in the ITRF97 reference frame. The antenna phase centre offsets and elevation-dependent variations are taken from the absolute calibration models of Geo++ (Wübbena 2003; Wübbena et al. 2003), whose azimuth-dependent variations have been averaged. We used a cutoff angle of 10°, which has been shown to be near optimum for regional networks (Görres and Campbell 1998). Tropospheric zenith delays are estimated for each site and every 3-h interval. The Gamit treatment provides two daily solutions with loose constraints on all estimated parameters, respectively, with floating and fixed (integer) ambiguities. Owing to its higher quality, the fixed ambiguity solution was used in the Globk combinations.

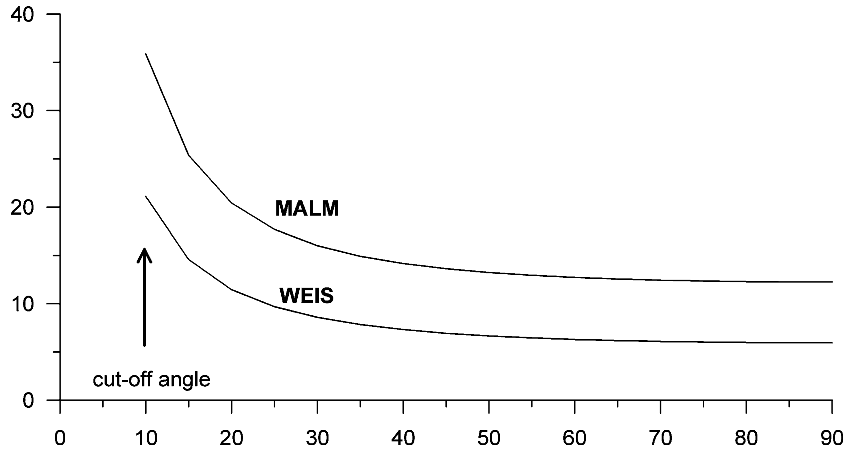
Two processing strategies have been tested, either including the orbit parameters with tight constraints in the adjustment or keeping the satellite orbits fixed on the positions integrated from the estimated initial conditions. The latter choice yielded more consistent final solutions and was retained.

The Globk processing step allows the combination of individual session solutions. In a first stage, the three or more sessions of a campaign epoch were combined. Kalman filtering gave an insight into the repeatability of daily solutions used as quasi-observations and, from the daily estimated station coordinates and the associated full covariance matrices, yielded campaign solutions for which we still applied loose constraints on the IGS site coordinates but tighter ones on the earth orientation parameters. Then, the campaign solutions were in turn combined as quasi-observations to obtain estimates of the site velocities. In this last stage, we not only constrained strongly most IGS site coordinates and velocities, but we also fixed the BRUS station, which is the IGS site nearest to the HARD network. Using a terrestrial fixed reference point further improves the precision on the intra-HARD baselines with respect to the level obtained within the remote reference frame of the fixed orbits. As a Markov process noise may be added in the Globk analysis (Herring 1999), we also modelled the station coordinate variations (except BRUS) as a random walk for which various values of the power spectral density of the driving white noise process were tested.

Results

Daily solutions resolve generally all but a few ambiguities on the HARD baselines and the statistics of the one-way phase residuals after a first adjustment and postfit data cleaning displays daily rms values in the range of 6–8 mm, bearing witness to very good solutions. Only MALM persistently shows postfit residuals around 11 mm. At this stage, the uncertainties in the baselines are 1–2 mm for the N and E components and 3–6 mm for the up component. An additional information derived from one-way phase postfit residuals is the standard deviation and the elevation-dependent parameter for 'a priori' (in terms of a later run) receiver measurement error models in the form $e=\sqrt{a^2+b^2/\sin^2[\mathrm{elev}]}$, used for data weighting in a second adjustment (King and Bock 1998) (Fig. 3). The

Fig. 3 A priori (in terms of a second program run) receiver measurement elevation-dependent errors at the MALM and WEIS sites for the day 78 of 2002



site ranking on the basis of these error models is consistent for all daily sessions from 1999 to 2003, and reflects site and instrumentation characteristics, from which it appears again that the MALM station is the noisiest, followed by NIVE and RECH (see Table 2 for example).

At the campaign level, with the fixed orbit option, the uncertainties on the HARD baseline up components lie in the range of 1.7–3.8 mm (1.6–4.8 mm for the longer baselines between the IGS stations included in the analysis). Except for slightly worse values resulting from the peak ionospheric perturbation in early spring of 2000, all surveys are of similar quality.

Considering the daily repeatability within each campaign under the conditions of a global solution with BRUS fixed and the other IGS stations tightly constrained, the same uncertainties fall between 1.5 mm and 3.8 mm (as also do the uncertainties on the height of individual sites). On a station-by-station basis, one will note that REID and especially NIVE (with daily variations of 25 mm in the up component) are the only disturbed sites during the 1999 survey. In 2000, WEIS shows daily height variations up to 22 mm. In 2002, WELK and RIGI display a min-max range of their up component respectively of 19 and 16 mm while in 2003, MALM, RIGI and WEIS show min-max ranges of ~15 mm, possibly linked to bad meteorological conditions during one night of the campaign. All other daily variations do not exceed ~5 mm around the mean. Moreover, the site noise revealed by the receiver measurement error models of some stations appears to have no particular influence on the stability of their daily solution.

Table 2 A priori receiver measurement errors of the HARD sites

Station	a	b
ANDR	6.63	3.57
BRUS	6.12	4.42
GRAS	4.59	3.23
HERS	4.08	2.89
KALT	4.59	3.91
KOSG	5.78	3.23
MALM	10.71	5.95
MEMB	4.93	3.74
NIVE	11.73	3.23
RECH	11.05	3.40
REID	7.99	5.27
RIGI	6.97	4.42
WAIM	9.01	4.08
WAVR	5.44	3.57
WEIS	4.76	3.57
WELK	6.29	4.25
WTZR	5.78	4.42

The standard deviations and elevation-dependent parameters (in mm) corresponding to the error model $\sigma = \sqrt{(a^2 + b^2 / \sin^2 [\text{elev}])}$ are based on postfit one-way residuals statistics. The following typical values were calculated for day 78 of 2002. Averaging on all available sessions from 1999 to 2003, MALM is the noisiest station, and especially the most sensitive to elevation-dependent errors

Finally, three versions of the whole 1999–2003 solution may be considered for the dicussion. The first one, in which we only allow for white noise in the site coordinate stochastic variations, yielded the differential motion rates listed in Table 3A. The 1σ uncertainties on the up component of the baselines are in the range of 1.3–3.0 mm while the uncertainties on their estimated velocities range from 0.6 mm/year to 1.3 mm/year. They are formal errors resulting from the propagation of the a priori errors assigned to the phase observations on the basis of postfit one-way residuals of a first run of the daily sessions and, in this sense, may appear realistic. However, weighted linear fits to the 1999–2003 time series one component at a time (in particular the up component of the individual baselines presented in the Fig. 4a), despite defining more or less similar motion rates, yield much more conservative uncertainties (between 0.6 mm/year and 9.0 mm/year, but mostly 1–4 mm/year). This may be the case because these fits reflect the full scatter of the campaign solutions (Table 3B). Applying to the site positions a random walk noise with power spectral densities successively corresponding to a noise source of 1 mm/√year, 5 mm/√year and 10 mm/√year, Kalman filtering showed that the first option (noise of 1 mm/√year), fairly realistic in terms of random walk noise alone (Langbein and Johnson 1997), yielded also consistent velocities. In this solution, the velocity uncertainties are in the range of 0.9–1.5 mm/year, about the same as in the solution

Table 3 Baseline up component rates of change

Site	A		B		C	
	UP rate (mm/year)	σ (mm/year)	UP rate (mm/year)	σ (mm/year)	UP rate (mm/year)	σ (mm/year)
BRUS	−1.87	0.70	−1.83	0.77	−2.26	0.98
ANDR	0.78	0.72	1.71	2.25	1.13	1.02
KALT	−1.27	0.71	−1.39	0.72	−1.33	1.01
MALM	3.19	0.94	3.22	1.20	3.16	1.18
MEMB	−2.59	0.87	−3.00	0.99	−2.58	1.17
NIVE	4.03	1.04	3.64	2.86	4.03	1.30
RECH	−2.00	0.75	−3.06	1.93	−2.35	1.04
REID	−1.31	0.79	−1.21	2.15	−1.35	1.06
RIGI	−1.31	0.68	−1.35	1.54	−1.32	0.99
WAIM	−2.46	1.03	−2.76	1.20	−2.49	1.29
WAVR	−2.53	0.88	−3.27	1.07	−2.63	1.17
WELK	−7.73	0.81	−8.61	4.14	−8.02	1.08

The differential rates are presented for the up component of the HARD sites with reference to WEIS. The relative rate of change of the fixed reference station of BRUS is also given with respect to WEIS. In A, these values result from a Kalman filtering with pure white noise. In B, they come from individual (one component at a time) weighted linear fits. In C, we include another stochastic component in the filtering by applying a Markov process noise corresponding to a 1 mm/√year and 0.4 mm/√year constraint respectively on the up and north/east coordinates of the stations

involving white noise only, and the estimated up/down baseline velocities are also similar to those obtained in the two previous estimates (Table 3C).

Theoretically, the solutions provided by the Kalman filters are more rigorous since they account for all the correlations between the sites and any temporal correlations as well and, as far as the process noise model used is correct, the last presented solution (Table 3c) is the most appropriate for a geological and geodynamical interpretation. However, whereas Langbein and Johnson (1997) suggest that the time-correlated noise affecting horizontal measurements could be of the random walk type only, Johnson and Agnew (1997) claim exactly the contrary for the noise signature in GPS-derived vertical motions and Mao et al. (1999) conclude that the most appropriate model to account for the noise characteristics of all three (north, east *and up*) components of GPS time series is a combination of white noise and flicker noise. These authors propose the following approximate expression for the total error on velocity

$$\sigma_r = \left[\frac{12\sigma_w^2}{gT^3} + \frac{a\sigma_f^2}{g^b T^2} + \frac{\sigma_{rw}^2}{T}\right]^{1/2}$$

where g is the number of measurements per year, T the total time span in years, σ_w and σ_f the magnitudes of white and flicker noise in mm, σ_{rw} the random walk noise in mm/√year, and a and b are empirical constants which they fix, respectively, at 1.78 and 0.22. This yields an uncertainty of ~2.7 mm/year on the up component motion rate of the HARD short baselines, based on the empirical values of 4 mm, 6 mm, and 1 mm, respectively, for the white noise, flicker noise and random walk noise amplitudes of the campaign solutions. In the following discussion, we rely therefore on the rate estimates of the third solution (Table 3C), keeping in mind that they are probably affected by a weakly defined noise and resulting high uncertainties.

Discussion

The reasoning above makes obvious that the time span of 4 years covered and the results obtained so far in the HARD project are not sufficient to draw any conclusion regarding possible differential motions of tectonic origin, especially with respect to vertical displacements. The investigated vertical tectonic rates are believed not to exceed 0.5 mm/year, so that the short-term displacements that they could induce are at least one order of magnitude lower than the noise in height change of near-surface origin. The high vertical rates produced by our solutions either result from systematic effects in the geodetic analysis and/or reflect the influence of shallow causes on ground motion.

Campaign-style monitoring and undesired effects

With regard to the point of obtaining reliable data in a reasonable period of time through campaign-mode monitoring of ground motion, we can obtain an approximate idea of the short-term repeatability of daily solutions (better than 5 mm in the up component of most baselines) from surveys which lasted between 3 days and 6 days, but the seasonal variations of these solutions cannot be picked up by such a mode of measurement. However, the inclusion of tropospheric parameters into the set of computed parameters should have strongly reduced the influence of seasonal and annual variations in tropospheric conditions on the solutions.

Another systematic effect might be caused by the type of our GPS monuments. Though the buildings on which the GPS antennas are installed have been chosen old enough to have settled, we cannot a priori preclude some residual monument instability and a possible thermal dilatation effect. Actually, the latter factor appears

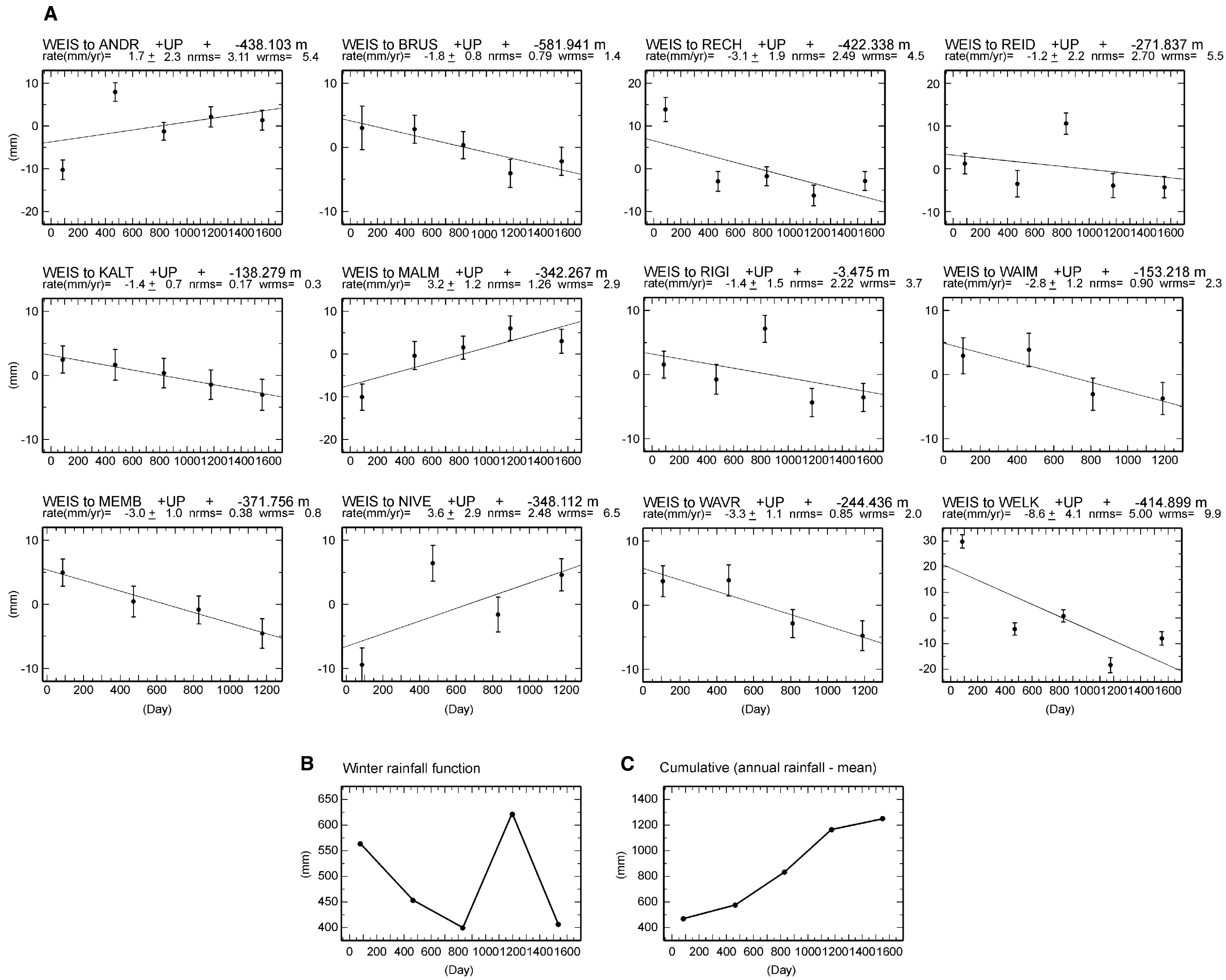


Fig. 4 **a** Time series of the up component of intra-HARD baselines. The reference station is WEIS, located at 700 m elevation at the top of the Weisserstein massif in western Eifel. The relative displacement of WEIS with respect to the fixed station of BRUS is also presented. The sign of the indicated differences in elevation and rates describes the situation of the second end of the baselines with respect to the first one, i.e. WEIS. The figured individual weighted linear fits correspond to the solution B velocities of Table 3. Day 0 is 1 January 1999, except for WAIM and WAVR (day 0 = 1 January 2000). *Bottom line*. Diagrams of the winter rainfall curve $f = \sum_{m=-3}^{-1} P_m + 0.5 \sum_{m=-6}^{-4} P_m$ (**b**) (see text for explanation) and of the cumulative deviation from the mean of the annual rainfall (**c**), used as proxies, respectively, for the degree of spring drying off of the soil and subsoil at the time of the surveys and the long-term groundwater level evolution. Rainfall data from Thimister

irrelevant, due to the thermal inertia of the buildings and to continuous heating or air conditioning, which keeps them at a more or less constant temperature throughout the year.

More generally, for true ground displacements of non-tectonic origin, the main seasonal influences are linked to variations in continental water, through swelling and shrinking of the soil and water loading (Zerbini et al. 2001; Van Dam et al. 2001). By carrying out the surveys always in the same season, we certainly minimized the unknown impact of seasonality on our GPS results, thus reducing aliasing problems in the incipient time series. However, yearly differences in rainfall and subsequently varying groundwater level and soil moisture have been shown to cause longer-wavelength noise superimposed on the seasonal signal in vertical motion, with sharp spatial contrast at the local scale determining high differential rates (Demoulin and Collignon 2002). In the case of campaign measurements, and since the response of each site to the influence of continental water is particular, we could try to model it only after at least seven to eight campaigns, a minimum number to look reliably for correlation between vertical ground displacement and some proxy of the groundwater level variations. Nevertheless, a first evaluation of the role of groundwater on surface motion in the study area will hopefully be gained in the near future from three stations of the WALCORS permanent GPS network of the Walloon region, which are to be put into service in September 2003 (Collignon A, oral communication).

In looking for geodetic artefacts or errors due to mismodelling or lack of modelling of some effects, we have to take into account the temporal linearity revealed by the campaign solutions for many HARD baselines (Fig. 4), which implies that the un- or mismodelled parameter(s) would have a systematic effect through gradual change. At first hand, it seems improbable that progressive modifications could occur in the multipath environment of the sites since all surveys were carried out in the same season, without alteration of the immediate surroundings of the antennas or any vegetation differences. Although the zenithal tropospheric path delays are treated as unknowns by Gamit, their mismodelling in some stages of the processing could also involve errors of a few millimetres in the up component of the sites. Indeed, the zenithal delays are estimated from slant-range delays, which may be strongly biased by specific meteorological conditions, in particular for low elevation signals. However, in this case, one would expect some correlation between the biased velocities and the site elevation, which does not exist at all. As for ageing of the electronics of receivers and antennas, it certainly will hardly lead to so regular patterns of change. Likewise, owing to the starting day of the successive campaigns randomly varying between March 15 and April 15, the yearly changes in GPS orbital constellation, influencing the solutions through miscalibrated antenna PCVs, should not have a systematic character. The other factors entering into the data processing (satellite orbits, reference frame, earth orientation parameters) have no significant influence on the very short HARD baselines. Finally, it is known from the comparison of time series of permanent GPS sites computed by various centres that the 'analysis noise' in a general sense may produce an artificial, steadily increasing or decreasing velocity component (Gandolfi et al. 2003), so that we have to be extremely careful with the uncertainty still affecting results from only five epochs. Nevertheless, owing to the small size of the network, we are led to believe that the main trends illustrated by the Fig. 4 are plausibly not artefacts or systematic mismodelling effects.

Observed motions: style and causes

If we proceed on the basis of this conclusion, then we are faced so far with results in which near-surface influences on vertical motion rates are probably considerable and, in the absence of any information on the storage of water in the soil and subsoil, we can only search site by site for trends of motion which would undoubtedly depart from a concomitant rainfall curve. The Fig. 4b presents this curve for the rainfall function

$$f = \sum_{m=-3}^{-1} P_m + 0.5 \sum_{m=-6}^{-4} P_m$$

which involves the monthly precipitation P_m of the last 6 months before the survey (therefore including winter rainfall) and whose variability has proved to correlate best with the variability of ground height changes in the region (Demoulin and Collignon 2002). Rainfall data are collected at the Thimister meteorological station, located between the ANDR and WELK sites of the HARD network and roughly reflect the annual relative variations of winter rainfall amount over the whole network. The few available data points indicate no relationship between the rainfall curve and the vertical displacements of the sites, which seem therefore not to be determined primarily by water in the soil and shallow subsoil.

Consider first the behaviour of the WEIS site with respect to BRUS, an IGS site at a distance of 150 km, whose coordinates and velocities have been fixed to their ITRF97 values for computing the HARD global solution. The relative uplift of WEIS is fairly regular (Fig. 4a), at a rate of 2.3 ± 1.0 mm/year (according to the adopted solution of Table 3C), corresponding to an absolute (ITRF97) rate of 2.9 mm/year. Considering the individual fit to the 1999–2003 time series of the up component of the BRUS-WEIS baseline, we obtain a likewise linear, but lower rate of 2.5 mm/year. This semi-decadal evolution, unaffected by erratic short-term near-surface influences, makes WEIS a good reference point for commenting on intra-HARD differential motions. However, note that such a motion rate, two times greater than the one inferred from levelling comparison (Mälzer et al. 1983), is also one order of magnitude higher than the maximum rate of Quaternary uplift deduced from river terrace analysis by Meyer and Stets (1998) for the western Eifel. Despite the regularity of that decadal trend, it should most probably receive a non-tectonic explanation.

Other HARD sites belonging to the same geological area show motion rates significantly different, but as regular temporal behaviours, compared with WEIS. The nearby site of KALT, e.g., is uplifting at a rate lower by 1.3 mm/year, this differential behaviour being remarkably constant from 1999 to 2003 and similar to what Görres and Campbell (1998) observed between 1992 and 1997. However, the recent results of another analysis with the Bernese GPS software covering 7 years from 1995 to 2002 suggest that no significant relative motion exists between KALT and WEIS (Kötter 2003). The WAIM and WAVR sites are also interesting, both showing an identical evolution. Beyond a marked jump due to a change of antenna configuration between 1999 and 2000 (the WAIM and WAVR diagrams of Fig. 4a omit the 1999 epoch), they constantly subside from 2000 to 2003 with respect to WEIS at rates, respectively, of about 2.5 mm/year and 2.6 mm/year. Two further sites located within the Stavelot massif also display fairly regular trends. MALM, situated in the alluvial plain of the Warche river in the Permian Malmédy graben, is moving up at a relative rate of 3.2 mm/year and MEMB, in the northern part of the massif, is subsiding at a rate of 2.6 mm/year relative to WEIS. The absolute rate of 0.4 mm/year of MEMB is notably lower than the

~2.0 mm/year recently calculated by Van Camp et al. (2003) on the basis of a time series of weekly solutions between 1997 and 2001.

Basically, the two main characteristics of this subset of HARD sites are, on the one hand, rather high apparent rates of vertical motion and, on the other, a consistent evolution over the period covered by the five surveys. If real, these features suggest that, when looking for tectonic signals in decadal records, one may also encounter linear motion trends of near-surface origin lasting several years. Such an influence on ground movement could be exerted by, e.g., a long-term rise or lowering of the groundwater level whose spatially varying amplitude would explain the between-site sharp contrasts in rate. The cumulative deviation from the mean of the annual rainfall in Thimister is given in the Fig. 4 as the only available, very rough proxy for the long-term groundwater level evolution. Whereas the variability in ground height change described by Demoulin and Collignon (2002) as a response to the rainfall curve mentioned above has white noise characteristics corresponding to the yearly varying drying off of the soil and subsoil in the spring, the link to the long-term groundwater level evolution emerging from the HARD results reveals the time-correlated effect of the infiltrated part of the precipitations on ground displacement.

As for the remaining sites, similar trends are observed in most cases, provided the outliers are removed. Many of these outliers are associated with the 2000 campaign, when the ionospheric conditions were the worst. The only really erratic station is WELK, which also displays the highest subsidence rate of 8.0 mm/year. As suggested by newly formed cracks, this subsidence could be related to karstic phenomena in the Dinantian limestone bedrock affecting the building on which the GPS antenna is installed.

Conclusion

The analysis of the five annual GPS surveys currently available has demonstrated that most sites of the HARD network yield results of good quality, appropriate for determination of true vertical ground motion. NIVE is the only unsatisfying station in terms of repeatability at the day and campaign levels. The poor repeatability of WELK at the global solution level and its high subsidence rate estimate make it another unreliable site for looking for tectonic displacements. The ten other GPS stations record temporally consistent but spatially discordant rate information. If real, these high motion rates are undoubtedly linked to near-surface causes which interfere with, and often conceal a possible tectonic influence. Therefore, not only do we need to carry out more surveys covering a timespan of at least 10 years in order to improve the rate estimates and decrease the associated uncertainty level, but we also should model the long-term variations of the groundwater level at individual sites so as to subtract their impact on ground motion from the trend in the time series. Using permanent GPS stations of the WALCORS network will allow us to rapidly identify seasonal effects but, in the absence of direct groundwater data, separating long term influences of near-surface and tectonic origin can also be attempted by combining GPS data with gravity measurements (less prone to monument instability problems, but superposing mass and ground displacement effects). This is why in 2003, we started coupled gravimetric and GPS campaigns with the collaboration of the Royal Observatory of Belgium. Another question which is currently investigated concerns errors resulting from the inherent data editing (i.e., deleting, weighting,...).

Finally, in view of the short data span of 4 years (five epochs), any tectonic discussion of the rate estimates obtained from yearly GPS campaigns has to be considered with care until further epochs are available. We may note at most that all sites located in NE Ardenne are uplifting with respect to Brussels and to most of the sites situated in the northern foreland of the massif. This is qualitatively consistent with geological data and levelling results.

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