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RELIABILITY OF GPS DATA FOR GEODYNAMIC STUDIES CASE STUDY: SUDETEN AREA, THE BOHEMIAN MASSIF

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ABSTRACT

A reliability of site movement assessments determined from GPS data monitored during eight two-day epoch measurements on the regional geodynamic EAST SUDETEN network (the Bohemian Massif, Central Europe) is discussed in details. Statistical tests of site positions processed by the BERNESE GPS software, their linear approximations for site movement velocity assessments and an establishment of probabilistic thresholds for reliability of the GPS data for regional geodynamic studies are delivered. The thresholds define necessary observation periods for annual epoch measurements performed on the networks with aim to obtain reliable movement estimates for geodynamic studies.

KEYWORDS: GPS epoch measurements, site velocity, reliability of data, the Bohemian Massif

1. INTRODUCTION

Recent satellite geodesy methods, mainly the global position system technologies (GPS), are broadly applied in geodynamic studies of global, continental, regional and local scales. Nowadays, motion velocities of individual plates and/or sub-plates can be assessed in high accuracy because of a lot of permanent GPS stations over the word.

Slightly another situation arises when motions of fundamental geological structures within an individual plate are taken into account. Each plate consists of a good number of different structural units that have been developed and mutually acted each to other over their existence. These units have created intra-plates and other big blocks with their own subsidiary motions in regard to the general plate motion. To indicate such intra-plate motions among these structural units and/or even inner structural block motions, the GPS observations should be performed on networks with relatively dense site spreading to cover investigated structures and neighbouring geological units. GPS epoch measurements on regional networks have specifics that influence their data processing and, naturally, a reliability of individual site motion determinations.

This paper summarizes GPS data processing experience of eight epoch measurements on the regional EAST SUDETEN network sites, placed in the Bohemian Massif (Variscides) within a close neighbouring to the East European Craton, the Alps and the West Carpathians (Fig. 1) and focuses mainly on reliability evaluation of motions determined for regional geodynamic studies.

2. GPS REGIONAL NETWORK AND GEOLOGICAL STRUCTURES

Areal configuration of network sites is an important step that affects substantially consequent geodynamic interpretations of the area. For that reason, it is highly effective efore individual network site placement to collect all available geological materials, geophysical and geodetic data and to analyse them from geodynamic viewpoints. As a result of this analysis a preliminary study of Neogene-Quaternary movements expected among the structures should be compiled. Then the network sites should be located at representative places of the area to detect the expected geodynamic pattern of regional geological structures and investigated tectonic zones.

Our case study network is located in the Sudetic unit of the Bohemian Massif which of eastern part is abutted by two fundamental European geological units: the Alpine-Himalayan orogenic structures and the East European Platform. The area is still under a dynamic influence of the latest Alpine-Himalayan orogenic phase. It is expected that the eastern part of the Bohemian Massif, the Moravo-Silesian region, and the Polish part of the Sudeten together with the

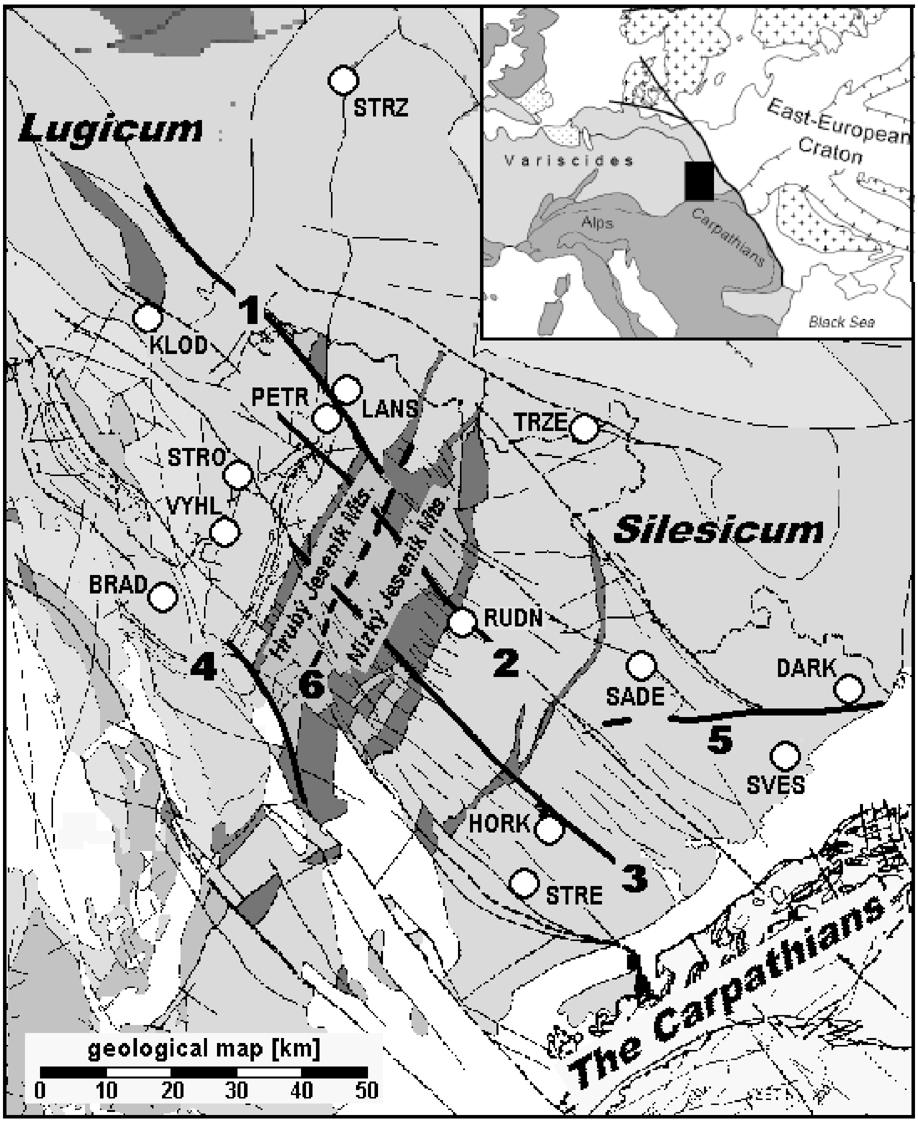

Fig. 1 Locations of the East Sudeten network sites in the Bohemian Massif (Central Europe) and tectonic faults: 1 – Marginal Sudetic fault, 2 – Bělá fault, 3- Klepáčov fault, 4 – Bušín fault, 5 – Opatovice fault zone, and 6 – Červená hora fault zone.

Fore-Sudetic block have even now active collision sections, where young and old geological structures interact (Schenk et al., 1998b, 2003; Cacoń and Dyjor, 2000).

The analysis of expected geodynamic movements in the Moravo-Silesian unit will not be discussed in this paper, only the positions of individual East Sudeten network sites selected with respect to structural blocks and fault zones which are drawn in Figure 1. In the area two sets of fault zones can be seen. One tectonic system belongs to the Sudetic NW-SE faults (the Main Sudetic, the Marginal Sudetic, the Bělá and Klepáčov faults, etc.) and the second one to the NNE-SSW Moravo-Silesian tectonics within that dominant thrust zones exist (e.g. the Ramzová and Červená hora thrust zones). To detect the recent geodynamic movements among structural blocks and along the fault zones, the GPS observation sites of the East Sudeten network were placed roughly to two SW-NE belts crossing the east and west marginal parts of the area studied oriented more or less perpendicularly to the Sudetic faults.

Field inspection of the network area allowed places for concrete monuments for GPS antenna installations to be embedded firmly into basement rocks. Such network monuments ensure long-term site stabilities and give a guarantee that any unexpected tilting and/or deformation processes caused in soils and in upper parts of weathered rocks will not affect individual epoch GPS measurements.

3. GPS EPOCH MEASUREMENTS

The basic set of concrete site monuments of the East Sudeten network (Fig. 1) was built in 1997 and consists of sites located both in the Czech (Schenk et al., 1998a) and the Polish (Cacoń et al., 1998)

Table 1 GPS epochs performed on the regional EAST SUDETEN geodynamic network.

Epoch #	Date	DOY
1	1997, August 29-31	241-243
2	1998, September 19-20	262-263
3	1999, September 11-12	254-255
4	2000, September 2-3	246-247
5	2001, September 8-9	251-252
6	2002, September 14-15	257-258
7	2003, September 6-7	249-250
8	2004, September 5-6	248-249

territories. Even if later a few other sites were added, in this paper the main attention is given just only to the basic site set to have homogeneous and relatively long-term GPS data sets.

The GPS epoch measurements on the EAST SUDETEN regional network have been performed annually always for two full GPS days mostly with the geodetic Ashtech equipments with every antenna fixed by a centring screw on the top of concrete site monument. All epochs were realized in the same yearly season to diminish main tropospheric changes occurring during a year. The satellite signals were monitored always by the same GPS antenna at the same site to exclude undesirable antenna phase-centre effects (Cacoń, 1998; Schenk et al., 1999, 2000, 2002). Sampling rate of monitored GPS satellite signals was 30 seconds to be easily linked to neighbouring permanent GPS observatories. Since a few receivers had 1MB internal memories only, thus two interruptions had to be inserted into the GPS signals monitoring to download recorded data to portable PCs. The interruptions were performed in accordance with the superposition of the minimal DOP and the maximal PDOP. List of annual epochs 1997-2004 performed on 10 Czech sites (BRAD, DARK, HORK, LANS, PETR, RUDN, SADE, STRE, SVES, VYHL) and on 5 Polish sites (KLOD, STRO, STRZ, TRZE, WROC) is in Table 1.

To ensure a high standard of the GPS observations and to guarantee the maximum possible quality of data processing, a quality assurance program for GPS epoch measurements had been adopted and strictly kept for all regional geodynamic investigations.

4. GPS DATA PROCESSING

The main principles of the movement velocity estimation for individual network sites in the global ITRF2000 (Altamini et al., 2002) and local reference frame give the following steps:

- The only identical baseline scheme for all GPS sessions,
- Independent, minimum constrained solution of each session using reference-point ITRF2000 coordinates, suitable for the measurement epoch,
- Transfer of the reference-point ITRF2000 coordinates from the reference epoch 1997,0 to each session epochs,
- Similarity transformation of each session results (the step 2) to the reference frame created by reference-point coordinates (the step 3) using "free network" constraint conditions,
- ITRF2000 velocity estimation of the network sites fixing (or weighting) the reference-point coordinates and velocities. Proper variance components of parameters was estimated by the unit weights scaling (Braun, 2002),

4.1. REFERENCE FRAME

Modern geodetic reference systems are conceived as reference frames for stations to unify their position coordinates and velocities. By this way the International GPS Service (IGS) global network and as well the European regional EUREF Permanent Network (EPN) meet these conditions. Their main products are (a) weekly estimates of tracking station coordinates and (b) combined solutions in the Software Independent Exchange Format (SINEX) (Bruyninx and Roosbeek, 2002). These solutions allow the time series of coordinate changes of the EPN/IGS stations in the geocentric or the geodetic systems to be estimated (Dong et al., 2002; Borkowski et al., 2003). The coordinates and velocities of IGS/EPN stations in a specific ITRF2000 realization make up the data for linkage to regional and/or local GPS networks.

The method of the mean trend congruency analysis of week solutions of coordinate time series (Borkowski et al., 2003) was applied to choice of reference IGS/EPN permanent stations for regional geodynamic EAST SUDETEN network. Thus, the epoch data monitored on the EAST SUDETEN network were extended by observations of four EPN neighbouring permanent stations Borowiec (BOR1), Pecný (GOPE), Penc (PENC) and Wetzel (WTZR) - see Figure 2 (Schenk et al., 1999; Bosy et al., 2003).

4.2. EPOCH SOLUTION

The GPS data were converted into the Receiver Independent Exchange Format (RINEX), checked by

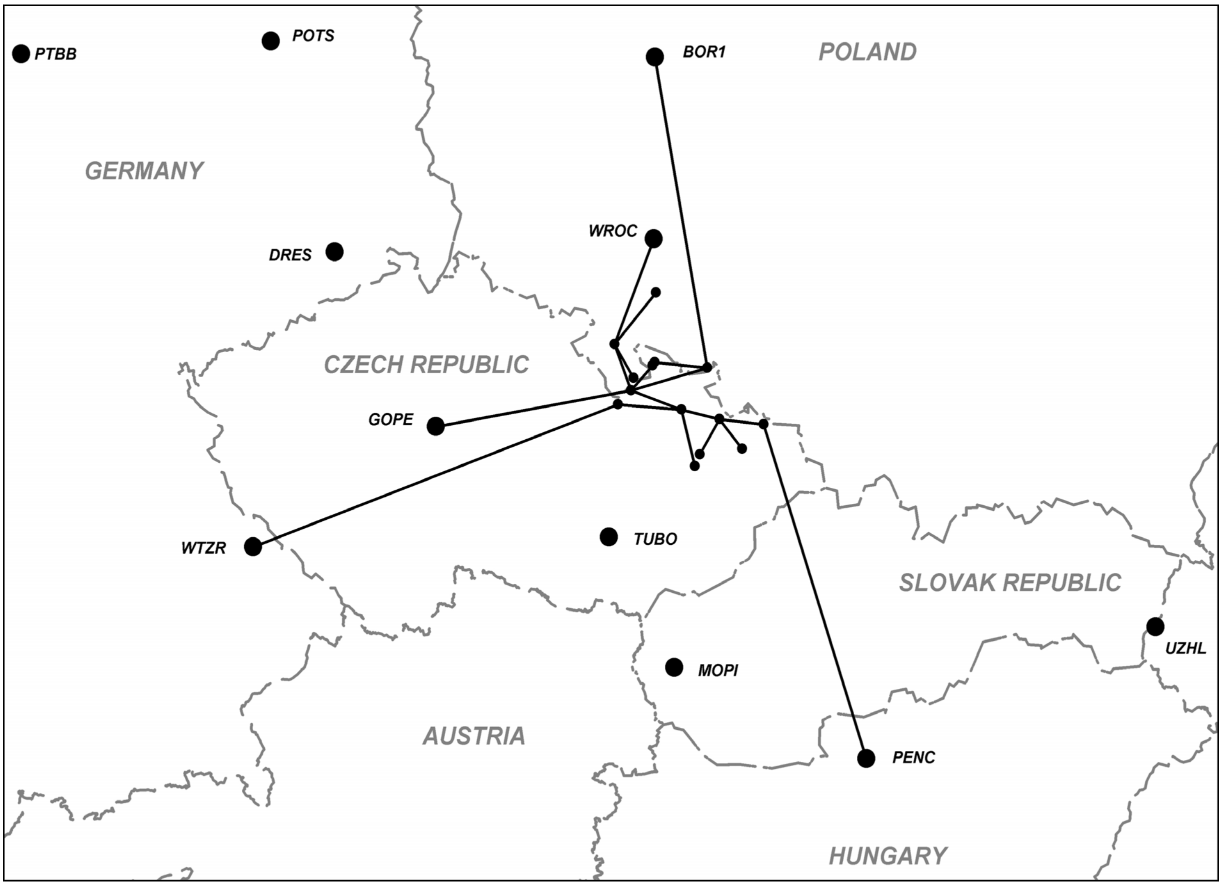

Fig. 2 The independent baselines used for GPS data processing on the East Sudeten network.

the TEQC (UNAVCO) software (Estey and Meertens, 1999) and pre-processed by the Bernese GPS Software v. 4.2. The main task of this process was to detect and repair cycle slips, and to remove bad data (e.g. data with high multipath). Independent baselines (Fig. 2) were created by the modified SHORTEST method (Hugentobler et al., 2001; Bosy et al., 2003).

The strategy of regional GPS networks (Habrich, 2002) was applied for the baseline processing with the following issues and assumptions (Bosy and Kontny, 1998; Bosy et al., 2003):

- local ionosphere model WUTE-L for a phase ambiguity resolution (Bosy et al., 2003),
- antenna phase centres calibrated according to the NGS (Mader, 1999),
- troposphere model – the Niell mapping function (Niell, 1996) and residual atmosphere zenith delays were estimated for one-hour intervals,
- precise ephemerides computed by the Center of Orbit Determination in Europe (CODE) to determine satellite positional data.

Two processing strategies were tested for the determination of ambiguities: the first strategy (S1) based on the Quasi-Ionospheric-Free (QIF) ambiguity resolution strategy (Mervart, 1995) and the second one (S2) based on the wide/narrow lane observable method (L5/L3). The first step in both strategies was identical

- ambiguity-free – ionosphere free linear combination solution for checking of coordinates accuracy.

Further, in the strategy S1

- the QIF resolution for both L1 and L2 ambiguities in the same run (WUTE-L ionosphere model)

was applied, while in the strategy S2

- wide-lane ambiguity resolution with all coordinates fixed (the WUTE-L ionosphere model) and
- ionosphere free linear combination solution introducing the resolved Wide-lane ambiguities and solution for the narrow-lane ambiguities

were used.

The strategy S1 assessed the ambiguity resolutions between 67 % to 86 % values, while the strategy S2 determined these resolutions into a narrower band of higher 83 % to 92 % values (Fig. 3). It can be seen that the strategy S2 increased the success rate of resolved ambiguities by several percent and thus the strategy S2 was chosen for subsequent processing.

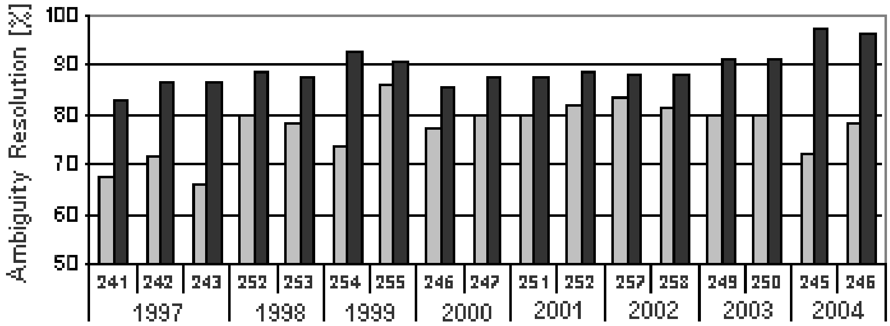

Fig. 3 Comparison of ambiguity solution results of the East Sudeten network for two strategies (QIF – grey and L5/L3 – black).

The GPS epoch data measured on the East Sudeten network during 1997–2004 were processed using the ADDNEQ module (Brockmann, 1997; Hugentobler et al., 2001). Connecting always both daily solutions together for one year, the geodetic coordinates of individual site for that year and their standard deviations $\sigma_{\Phi(B)}$ were calculated. Figure 4 shows non-weighted deviations $\sigma_{N(B)}$, $\sigma_{E(B)}$ and $\sigma_{Up(B)}$ of two-day 24-hour solutions of eight GPS campaigns.

Pronounced reductions of $\sigma_{N(B)}$, $\sigma_{E(B)}$ and $\sigma_{Up(B)}$ were reached already for the second and following subsequent GPS epochs because of methodological improvements introduced to the GPS field observations and data processing in 1998. They caused that $\sigma_{N(B)}$ and $\sigma_{E(B)}$ exceeded slightly 1 mm and $\sigma_{Up(B)}$ did not exceeded 5 mm in 1998-2002, except the 2002 epoch (8 mm), and since 2003 already $\sigma_{Up(B)}$ has not reached 2 mm.

Even if the first view to the $\sigma_{\Phi(B)}$ brings an image that they are not low enough for reliable applications in geodynamic studies, the next Paragraphs will clearly document that the movement velocities V_{Φ} and their related $\sigma_{V\Phi}$ determined from great number of annual epochs can give reliable geodynamic movements of individual structure tectonic blocks. For instance for the horizontal components four and more annual epochs and for vertical ones round seven and more epochs appear to be sufficient to obtain already stable and accurate movement trends.

4.3. *MOVEMENT VELOCITIES*

To estimate the movement velocity combinations of independent (24-hour) session solutions of selected epoch (n-years) was applied (Brockmann, 1997; Hugentobler et al., 2001).

Velocities of the East Sudeten network sites were computed in the reference frame ITRF2000 with the constrained ITRF coordinates and velocities of reference sites given by the International Earth Rotation Service (IERS) for combined solutions. Free network conditions for reference coordinates and velocities were applied. Then all the daily sessions were processed by the Bernese GPS software v. 4.2, ADDNEQ module (Braun, 2002), to estimate the velocity movements $V_{\Phi(B)}$ and their $\sigma_{V\Phi(B)}$ (Table 2).

4.4. *TESTS OF VELOCITIES DUE TO OUTLIERS*

When the GPS data monitored in several annual campaigns were processed by the Bernese GPS software v. 4.2 the changes in time series of individual sites (Fig. 5) could be found with respect to analyzed campaigns combination. To detect and assess a possible influence of outlier coordinates on individual time series of the East Sudeten sites, two approximation methods allowing an existence of the outliers were applied.

Estimators of the Least Squares method (LS) are strongly affected by outliers (Hampel et al., 1986). The most of the GPS professional software (e.g. Bernese GPS) uses the Least Squares method (LS) to estimate the coordinate and velocity components. To avoid outlier influences the methods of robust estimation, the Huber's method of M-estimation (M) (Huber, 1981) and the Least Median of Squares method (LMS) (Rousseeuw and Leroy, 1987) were tested. The time series of individual sites were calculated by the LS, M and LMS methods and the velocity differences $V_{\Phi(LS)}–V_{\Phi(M)}$ and $V_{\Phi(LS)}–V_{\Phi(LMS)}$ were compared (Table 3).

In dominant majority the horizontal velocity differences rarely reached 0.2 mm/year and the vertical ones 0.4 mm/year (Table 3). Only a few differences exceeded these values and if the difference appeared in one testing couple, it had not been detected in the second one. Nevertheless, as evident, that the velocity differences were approved to be significantly under allowable limits considered for precise GPS data.

5. SITE VELOCITY MOVEMENTS

Generally, standard procedures applied to the GPS data as the Bernese, Gamit/Globk, etc., calculate the geocentric and/or geodetic coordinates of

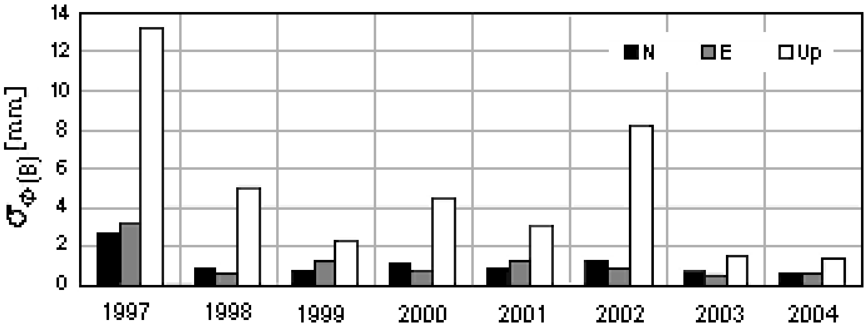

Fig. 4 Non-weighted $\sigma_{\Phi(B)}$ values for each year determined from two-day solutions in [mm].

Table 2 Velocities $V_{\Phi(B)}$ and their $\sigma_{V\Phi(B)}$, both given in [mm/yrs], for the EAST SUDETEN network sites determined from the 8-year annual GPS data solution of 1997–2004 epochs.

site	$V_{N(B)}$	$V_{E(B)}$	$V_{Up(B)}$	$\sigma_{VN(B)}$,	$\sigma_{VE(B)}$,	$\sigma_{VUp(B)}$,
BRAD	13.63	20.43	2.55	0.04	0.03	0.19
DARK	14.18	20.97	1.18	0.04	0.03	0.19
HORK	13.12	20.63	1.10	0.04	0.03	0.18
KLOD	16.15	21.04	3.37	0.04	0.03	0.19
LANS	13.32	20.47	0.63	0.04	0.03	0.20
PETR	11.63	20.17	0.95	0.04	0.03	0.19
RUDN	14.58	21.00	-0.65	0.04	0.03	0.18
SADE	13.03	21.30	-0.30	0.04	0.03	0.18
STRE	15.52	19.91	8.74	0.04	0.03	0.19
STRO	13.86	20.29	1.22	0.04	0.03	0.21
STRZ	14.72	21.19	0.12	0.05	0.03	0.25
SVES	13.81	21.41	8.85	0.04	0.03	0.21
TRZE	16.31	21.63	-2.18	0.04	0.03	0.20
VYHL	13.81	20.71	-0.25	0.04	0.03	0.18
WROC	14.35	19.76	-0.64	0.04	0.03	0.20

sites for which data sets were recorded during one or more DOYs sessions (Paragraph 3). In our case, the BERNESE output site coordinates and the other LS, M and LMS linear approximations (Paragraph 4) were analyzed to assess site velocity movement uncertainty.

For this purpose the following scheme of data set combinations of GPS data (Fig. 6) for the BERNESE processing was applied. Particular combinations for one-year intervals (6 sets of 2 annual epochs), two-year intervals (5 sets of 3 annual epochs) up to seven-year interval (1 set of 8 annual epochs) were processed separately. Thus, from every data set the site velocity movements $V_{s\Phi}$ and their $\sigma_{sV\Phi}$ were assessed; the example of the assessment is given for BRAD site in Tables 4 and 5.

This approach allowed all site values $V_{s\Phi}$ and $\sigma_{sV\Phi}$ to be assorted with respect to individual sites and to be ordered according to input data sets. The examples of the mean site values $V_{s\Phi(B)}$ and their mean standard deviations $\sigma_{sV\Phi(B)}$ for the BRAD site are in Table 4. The values $V_{s\Phi(B)}$ can be understood already as the first step in a determination of a reliable site movement velocity. Since the standard deviation $\sigma_{sV\Phi(B)}$ of $V_{s\Phi(B)}$ is assumed ordinarily as a “measure of variability”, and in our case it will be taken as a “measure of reliability”, the individual $V_{s\Phi(B)}$ and $\sigma_{sV\Phi(B)}$ values are written just in two lines under each framed area. Site annual movement velocities V_{Φ} for the BRAD site were determined also by the Least Squares (LS), M-Estimation (M) and Least Median of Squares (LMS) methods and obtained velocities $V_{\Phi(LN)}$, $V_{\Phi(M)}$, and $V_{\Phi(LMS)}$ are shown in Table 5.

If the $\sigma_{V\Phi(B)}$ and the $\sigma_{sV\Phi(B)}$ values are statistically processed for all network sites, one can find that the rate between both values varied in the interval of 4 to 15 and can be written in a form

$$\sigma_{V\Phi(B)} / \sigma_{sV\Phi(B)} = 17.8 \pm 2.2 - 1.7 \pm 0.3\ T \quad , \qquad (1)$$

where T [years] is a number of annual periods of the epoch solutions applied for the velocity determination.

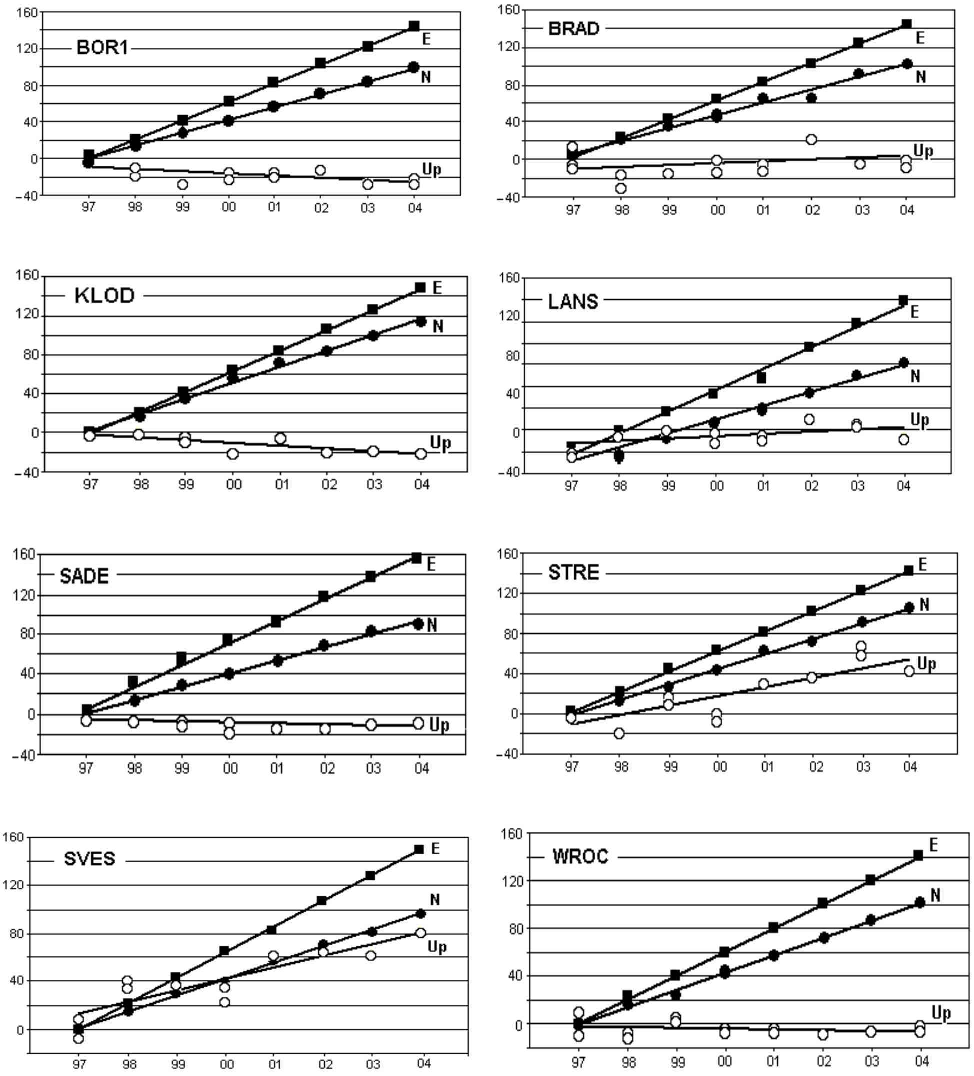

Fig. 5 Examples of the annual positional differences of the geodetic coordinates in [mm] for a few selected network sites.

The equation (1) is valid for the number of the observation period 3 ≥ T [years] ≥ 7 and for the rate $\sigma_{V\Phi(B)} / \sigma_{sV\Phi(B)}$ which varied in the interval values of 5.5 to 13. Since we understood the $\sigma_{sV\Phi(B)}$ as a measure of reliability then the rate of $\sigma_{V\Phi(B)} / \sigma_{sV\Phi(B)}$ can be taken as the very preliminary criterion for the reliability assessments of the site velocity movements $V_{\Phi(B)}$.

For example, if the $\sigma_{sVN(B)}$, $\sigma_{sVE(B)}$ and/or $\sigma_{sVUp(B)}$ are equal to or smaller than 0.1 mm/year then the site movement velocities $V_{sN(B)}$, $V_{sE(B)}$ and/or $V_{sUp(B)}$ are determined with accuracies that do not permit to change these values in future for more than 10 %. Site movement velocities assessed by this way would not be changed already for more than ±1 mm/year. Even if a scatter of the rate $\sigma_{V\Phi(B)} / \sigma_{sV\Phi(B)}$ exists (Eq. 1), we believe that this rate can help quickly to achieve reliability assessments of the $\sigma_{sV\Phi(B)}$ values.

The relationships of $\sigma_{sV\Phi}$ deviations for observation periods T [year] display exponential decreases (Fig. 7). To evaluate a rate of the decrease with increasing amount of epoch solutions, the $\sigma_{sV\Phi}$ values of all network sites were statistically processed and the following equation

$$\sigma_{sV\Phi} = a \exp(-b \times T) \qquad (2)$$

was introduced, where $\sigma_{sV\Phi}$ deviations are in [mm/year]. Individual relations of the $\sigma_{sVN}(T)$, $\sigma_{sVE}(T)$ and $\sigma_{sVUp}(T)$ obtained for the East Sudeten network sites are in Figure 7.

In previous paragraph linear approximations of the Least Squares (LS), the M-estimation (M) and the Least Median of Squares (LMS) methods were applied not only to check stability and reliability analyzed data but also to test a possibility to mitigate

Table 3 Velocity differences $V_{\Phi(LS)}–V_{\Phi(M)}$ and $V_{\Phi(LS)}–V_{\Phi(LMS)}$, where $V_{\Phi(LS)}$ velocity was determined by the Least Squares method, $V_{\Phi(M)}$ determined by the robust M-estimation method, and $V_{\Phi(LMS)}$ determined by the Least Median of Squares method.

SITE	LS - M [mm]			LS - LMS [mm]		
	$V_{N(LS)}–V_{N(M)}$	$V_{E(LS)}–V_{E(M)}$	$V_{Up(LS)}–V_{Up(M)}$	$V_{N(LS)}–V_{N(LMS)}$	$V_{E(LS)}–V_{E(LMS)}$	$V_{Up(LS)}–V_{Up(LMS)}$
BRAD	-0.1	0	0.2	0.5	0	0.1
DARK	-0.1	0.1	0.1	0	0	-1.3
HORK	0.1	0.1	-0.5	0	0.1	0
KLOD	-0.1	0	2.5	-0.3	0	0.1
LANS	-0.4	-0.2	-0.1	-1.7	-0.1	0.4
PETR	-0.1	-0.1	-0.1	0.5	-0.1	0
RUDN	0	-0.1	-0.5	-0.1	0	1
SADE	-0.2	0.3	1.5	0	0	0
STRE	0	0.1	0.4	0	0	3.1
STRO	0	0.1	0	0	0	0
STRZ	0	0.1	-0.3	0	0	0
SVES	0	-0.1	0.3	0	0	0
TRZE	-0.2	0.3	0.5	-0.1	0.2	0.1
VYHL	0	0.2	0.9	0.1	0.9	0.7
WROC	0.1	0	-0.2	-0.1	0	-0.2

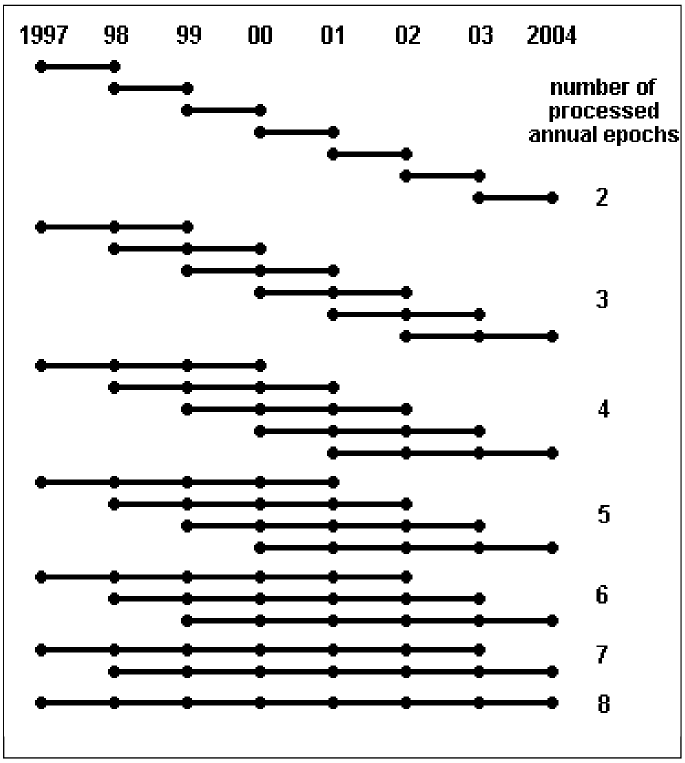

Fig. 6 Selection of epochs for the velocity calculations.

Table 4 Site velocity $V_{\Phi(B)}$ and their $\sigma_{V\Phi(B)}$, both in [mm/yr], for the BRAD site.

epoch	$V_{N(B)}$	$V_{E(B)}$	$V_{Up(B)}$	$\sigma_{VN(B)}$	$\sigma_{VE(B)}$	$\sigma_{VUp(B)}$
97-98	21.07	21.68	-13.94	0.40	0.28	1.84
98-99	13.10	20.15	14.15	0.41	0.28	1.86
99-00	10.12	22.92	3.25	0.42	0.30	1.89
00-01	18.41	17.80	-1.04	0.41	0.30	1.82
01-02	0.56	19.12	23.16	0.41	0.30	1.82
02-03	26.17	21.97	-16.87	0.41	0.30	1.83
03-04	10.84	20.27	-1.89	0.41	0.30	1.85
$V_{s\Phi(B)}$	14.32	20.56	0.97	0.41	0.29	1.84
$\sigma_{sV\Phi(B)}$	7.78	1.64	13.22			
97-99	17.27	21.04	-0.48	0.21	0.15	0.95
98-00	11.78	21.50	7.94	0.21	0.15	0.94
99-01	14.46	20.41	0.59	0.21	0.15	0.93
00-02	9.35	18.54	11.28	0.21	0.16	0.94
01-03	12.29	20.40	5.39	0.21	0.15	0.93
02-04	17.87	21.06	-9.30	0.19	0.14	0.86
$V_{s\Phi(B)}$	13.84	20.49	2.57	0.21	0.15	0.93
$\sigma_{sV\Phi(B)}$	3.03	0.95	6.67			
97-00	14.77	21.48	2.22	0.14	0.10	0.61
98-01	13.70	20.61	4.45	0.13	0.09	0.59
99-02	10.53	19.87	7.41	0.14	0.10	0.60
00-03	13.04	19.53	5.29	0.14	0.10	0.60
01-04	13.67	20.53	-0.52	0.12	0.09	0.53
$V_{s\Phi(B)}$	**13.14**	**20.40**	**3.77**	0.13	0.10	0.59
$\sigma_{sV\Phi(B)}$	1.42	0.67	2.71			
97-01	15.00	20.86	2.06	0.10	0.07	0.43
98-02	11.35	20.21	7.56	0.09	0.07	0.43
99-03	12.56	20.13	4.83	0.10	0.07	0.43
00-04	13.72	19.99	1.03	0.09	0.06	0.38
$V_{s\Phi(B)}$	**13.16**	**20.30**	**3.87**	0.10	0.07	0.42
$\sigma_{sV\Phi(B)}$	1.35	0.33	2.54			
97-02	12.92	20.52	5.10	0.07	0.05	0.33
98-03	12.57	20.28	5.79	0.07	0.05	0.33
99-04	13.25	20.25	1.86	0.07	0.05	0.29
$V_{s\Phi(B)}$	**12.91**	**20.35**	**4.25**	0.07	0.05	0.32
$\sigma_{sV\Phi(B)}$	0.28	0.12	1.71			
97-03	13.50	20.48	4.15	0.06	0.04	0.26
98-04	13.09	20.32	3.22	0.05	0.04	0.23
$V_{s\Phi(B)}$	**13.30**	**20.40**	**3.69**	0.06	0.04	0.25
$\sigma_{sV\Phi(B)}$	0.20	0.08	0.46			
97-04	**13.63**	**20.43**	**2.55**	0.04	0.03	0.19

Mean values $V_{s\Phi(B)}\approx$ *and* $\sigma_{sV\Phi(B)}\approx$ *were determined in accordance with the probability 10% thresholds for the possible site movements (see Paragraph 7); applied* $V_{\Phi(B)}$ *and* $\sigma_{V\Phi(B)}$ *values of four and more annual epoch solutions are marked in Table by the bold numbers.*

$V_{s\Phi(B)}\approx$	13.23	20.38	3.63
$\sigma_{sV\Phi(B)}\approx$	0.24	0.05	0.57

Table 5 Site annual movement velocities for the BRAD site obtained by the Least Squares (LS), M–Estimation (M) and Least Median of Squares (LMS) methods

	LN			**M**			**LMS**		
epoch	$V_{N(LN)}$	$V_{E(LN)}$	$V_{Up(LN)}$	$V_{N(M)}$	$V_{E(M)}$	$V_{Up(M)}$	$V_{N(LMS)}$	$V_{E(LMS)}$	$V_{Up(LMS)}$
97-98	22.2	22.4	-16.6	21.1	22.2	-16.4	21.0	21.9	-21.7
98-99	13.2	20.2	13.8	13.2	20.2	13.8	14.3	21.0	19.0
99-00	10.0	22.8	3.4	10.0	22.8	3.4	8.4	24.3	8.4
00-01	18.6	17.9	-0.3	18.6	17.9	-0.3	21.5	18	2.5
01-02	0.3	19.1	22.7	0.3	19.1	22.7	-0.5	19.2	26.1
02-03	26.4	21.8	-17.3	26.4	21.8	-17.3	26.9	22.4	-15.0
03-04	10.8	20.2	-2.1	10.8	20.2	-2.1	11.6	21.6	-7.0
$V_{s\Phi}$	**14.5**	**20.63**	**0.51**	**14.34**	**20.6**	**0.54**	**14.74**	**21.2**	**1.76**
$\sigma_{sV\Phi}$	**8.06**	**1.66**	**13.60**	**7.92**	**1.63**	**13.57**	**8.58**	**1.93**	**16.22**
97-99	18.1	21.4	-2.6	17.4	21.4	-1.9	18.9	21.8	-0.5
98-00	11.7	21.6	8.2	11.9	21.9	8.2	10.8	22.0	8.3
99-01	14.4	20.4	1.5	14.3	20.2	1.6	14.5	18.5	-0.9
00-02	9.5	18.7	11.1	9.3	18.7	11.6	8.4	18.7	14.2
01-03	13.1	20.5	2.8	13.2	20.5	2.6	13.3	20.8	2.0
02-04	18.4	21.1	-10.0	18.5	21.2	-10.2	18.6	21.5	-8.7
$V_{s\Phi}$	**14.2**	**20.62**	**1.83**	**14.1**	**20.65**	**1.98**	**14.08**	**20.55**	**2.4**
$\sigma_{sV\Phi}$	**3.23**	**0.96**	**6.92**	**3.14**	**1.04**	**7.01**	**3.82**	**1.43**	**7.27**
97-00	15.6	21.7	0.1	15.6	21.7	0.5	17.9	21.5	2.2
98-01	13.6	20.6	5.0	13.8	20.5	4.8	13.8	20.6	1.4
99-02	10.6	19.9	7.5	10.2	19.7	8.1	9.9	20.3	9.2
00-03	13.5	19.6	3.9	14.1	19.6	3.2	14.1	19.6	2.3
01-04	13.7	20.5	-0.7	12.9	20.5	0.6	12.7	20.6	1.7
$V_{s\Phi}$	**13.4**	**20.46**	**3.16**	**13.32**	**20.4**	**3.44**	**13.68**	**20.52**	**3.36**
$\sigma_{sV\Phi}$	**1.60**	**0.72**	**3.07**	**1.79**	**0.75**	**2.8**	**2.59**	**0.61**	**2.94**
97-01	15.7	20.9	0.6	15.6	20.9	1.1	15.6	21	1.7
98-02	11.3	20.2	7.8	11.3	20.1	7.9	11.0	20.5	7.5
99-03	12.9	20.0	4.0	13.2	20.0	2.7	13.7	20.2	1.7
$V_{s\Phi}$	13.7	19.9	1.3	13.7	19.9	1.1	12.7	19.7	1.2
$\sigma_{sV\Phi}$	**13.4**	**20.25**	**3.44**	**13.45**	**20.24**	**3.2**	**13.25**	**20.35**	**3.03**
σ	**1.58**	**0.39**	**2.83**	**1.53**	**0.40**	**2.79**	**1.67**	**0.47**	**2.59**
97-02	13.6	20.6	3.5	13.7	20.6	3.5	13.3	20.7	3.4
98-03	12.8	20.2	5.2	13.3	20.2	4.8	13.5	20.4	4.8
99-04	13.1	20.2	2.2	13.3	20.1	1.8	13.0	20.3	2.0
$V_{s\Phi}$	**13.17**	**20.33**	**3.63**	**13.43**	**20.3**	**3.37**	**13.27**	**20.47**	**3.4**
$\sigma_{sV\Phi}$	**0.33**	**0.19**	**1.23**	**0.19**	**0.22**	**1.23**	**0.21**	**0.17**	**1.14**
97-03	14.1	20.5	2.8	14.3	20.5	2.4	13.5	20.5	3.1
98-04	13.0	20.3	3.5	13.3	20.2	2.7	13.1	20.4	3.4
$V_{s\Phi}$	**13.55**	**20.4**	**3.15**	**13.8**	**20.35**	**2.55**	**13.3**	**20.45**	**3.25**
$\sigma_{sV\Phi}$	**0.55**	**0.1**	**0.35**	**0.5**	**0.15**	**0.15**	**0.2**	**0.05**	**0.15**
97-04	14.0	20.5	2.0	14.1	20.5	1.8	13.5	20.5	1.9

and/or to exclude outlier effects from approximations (Table 6). When individual values of $V_{s\Phi(LN)}$, $V_{s\Phi(M)}$, $V_{s\Phi(LMS)}$ and their related $\sigma_{sV\Phi(LN)}$, $\sigma_{sV\Phi(M)}$, $\sigma_{sV\Phi(LMS)}$ were compared with the $V_{s\Phi(B)}$ and $\sigma_{sV\Phi(B)}$ determined from the BERNESE approximations, insignificant differences among these values were found. Similarly, a comparison of four equations (2) for the $\sigma_{sV\Phi(B)}(T)$, $\sigma_{sV\Phi(LN)}(T)$, $\sigma_{sV\Phi(M)}(T)$ and $\sigma_{sV\Phi(LMS)}(T)$ obtained from all network sites confirmed the above mentioned statement: *a* and *b* coefficients of the equation (2) displayed unimportant differences (Table 7).

Table 8 gives average coefficients $\bar{a}$ and $\bar{b}$ of the equation (3) achieved by averaging the *a* and *b* coefficients of all linear statistical approximations above mentioned

$$\sigma_{sV\Phi} = \bar{a}\exp(-\bar{b}\times T) \quad . \qquad (3)$$

Table 6 Annual velocity movements for the BRAD site obtained by the Bernese GPS software, Least Square (LS), M–Estimation (M) and Least Median of Square (LMS) methods.

	BERNESE ADDNEQ module (v. 4.2)						**LS**						**M-**Estimation						**LMS**					
epoch	$V_{N(B)}$	$V_{E(B)}$	$V_{Up(B)}$	$\sigma_{VN(B)}$	$\sigma_{VE(B)}$	$\sigma_{VUp(B)}$	$V_{N(LS)}$	$V_{E(LS)}$	$V_{Up(LS)}$	$\sigma_{VN(LS)}$	$\sigma_{VE(LS)}$	$\sigma_{VUp(LS)}$	$V_{N(M)}$	$V_{E(M)}$	$V_{Up(M)}$	$\sigma_{VN(M)}$	$\sigma_{VE(M)}$	$\sigma_{VUp(M)}$	$V_{N(LMS)}$	$V_{E(LMS)}$	$V_{Up(LMS)}$	$\sigma_{VN(LMS)}$	$\sigma_{VE(LMS)}$	$\sigma_{VUp(LMS)}$
97-98	21.07	21.68	-13.94	0.40	0.28	1.84	22.20	22.40	-16.60	3.20	1.40	11.80	21.10	22.20	-16.40	2.40	1.40	11.60	21.00	21.90	-21.70	0.40	0.30	5.70
98-99	13.10	20.15	14.15	0.41	0.28	1.86	13.20	20.20	13.80	1.00	2.10	8.60	13.20	20.20	13.80	0.90	1.80	7.20	14.30	21.00	19.00	0.50	0.70	1.50
99-00	10.12	22.92	3.25	0.42	0.30	1.89	10.00	22.80	3.40	2.90	1.80	8.30	10.00	22.80	3.40	2.40	1.50	6.90	8.40	24.30	8.40	0.60	0.00	1.50
00-01	18.41	17.80	-1.04	0.41	0.30	1.82	18.60	17.90	-0.30	2.90	0.10	9.00	18.60	17.90	-0.30	2.50	0.10	7.90	21.50	18.00	2.50	0.90	0.00	3.60
01-02	0.56	19.12	23.16	0.41	0.30	1.82	0.30	19.10	22.70	1.10	0.20	4.40	0.30	19.10	22.70	0.90	0.10	3.60	-0.50	19.20	26.10	0.00	0.00	0.00
02-03	26.17	21.97	-16.87	0.41	0.30	1.83	26.40	21.80	-17.30	0.70	0.80	2.80	26.40	21.80	-17.30	0.60	0.70	2.30	26.90	22.40	-15.00	0.00	0.00	0.00
03-04	10.84	20.27	-1.89	0.41	0.30	1.85	10.80	20.20	-2.10	0.80	1.30	4.50	10.80	20.20	-2.10	0.70	1.20	4.10	11.60	21.60	-7.00	0.40	0.60	2.30
$V_{s\Phi}$	**14.32**	**20.56**	**0.97**	**0.41**	**0.29**	**1.84**	**14.50**	**20.63**	**0.51**	**1.80**	**1.10**	**7.06**	**14.34**	**20.60**	**0.54**	**1.49**	**0.97**	**6.23**	**14.74**	**21.20**	**1.76**	**0.40**	**0.23**	**2.09**
$\sigma_{sV\Phi}$	**7.78**	**1.64**	**13.22**				**8.06**	**1.66**	**13.60**				**7.92**	**1.63**	**13.56**				**8.58**	**1.93**	**16.22**			
97-99	17.27	21.04	-0.48	0.21	0.15	0.95	18.10	21.40	-2.60	1.40	0.70	5.60	17.40	21.40	-1.90	1.20	0.80	5.50	18.90	21.80	-0.50	0.20	0.10	1.70
98-00	11.78	21.50	7.94	0.21	0.15	0.94	11.70	21.60	8.20	1.70	0.90	3.60	11.90	21.90	8.20	1.70	0.60	3.70	10.80	22.00	8.30	1.00	0.10	0.94
99-01	14.46	20.41	0.59	0.21	0.15	0.93	14.40	20.40	1.50	1.90	0.90	3.10	14.30	20.20	1.60	1.80	0.80	3.00	14.50	18.50	-0.90	0.40	0.00	0.70
00-02	9.35	18.54	11.28	0.21	0.16	0.94	9.50	18.70	11.10	2.90	0.20	5.40	9.30	18.70	11.60	3.20	0.20	5.40	8.40	18.70	14.20	1.00	0.00	1.90
01-03	12.29	20.40	5.39	0.21	0.15	0.93	13.10	20.50	2.80	4.30	0.70	9.10	13.20	20.50	2.60	4.20	0.70	11.70	13.30	20.80	2.00	0.40	0.30	1.60
02-04	17.87	21.06	-9.30	0.19	0.14	0.86	18.40	21.10	-10.00	2.50	0.50	4.60	18.50	21.20	-10.20	1.90	0.50	5.20	18.60	21.50	-8.70	0.20	0.00	1.30
$V_{s\Phi}$	**13.84**	**20.49**	**2.57**	**0.21**	**0.15**	**0.93**	**14.20**	**20.62**	**1.83**	**2.45**	**0.65**	**5.23**	**14.10**	**20.65**	**1.98**	**2.33**	**0.60**	**5.75**	**14.08**	**20.55**	**2.40**	**0.53**	**0.08**	**1.36**
$\sigma_{sV\Phi}$	**3.03**	**0.95**	**6.67**				**3.23**	**0.96**	**6.92**				**3.14**	**1.04**	**7.01**				**3.82**	**1.43**	**7.27**			
97-00	14.77	21.48	2.22	0.14	0.10	0.61	15.60	21.70	0.10	1.50	0.40	3.70	15.60	21.70	0.50	1.60	0.40	3.70	17.90	21.50	2.20	0.30	0.10	0.50
98-01	13.70	20.61	4.45	0.13	0.09	0.59	13.60	20.60	5.00	1.00	0.50	2.10	13.80	20.50	4.80	0.90	0.40	2.10	13.80	20.60	1.40	0.40	0.20	0.40
99-02	10.53	19.87	7.41	0.14	0.10	0.60	10.60	19.90	7.50	1.40	0.60	3.00	10.20	19.70	8.10	1.40	0.60	4.20	9.90	20.30	9.20	0.20	0.20	0.40
00-03	13.04	19.53	5.29	0.14	0.10	0.60	13.50	19.60	3.90	2.10	0.40	4.70	14.10	19.60	3.20	2.10	0.30	5.20	14.10	19.60	2.30	0.30	0.00	1.00
01-04	13.67	20.53	-0.52	0.12	0.09	0.53	13.70	20.50	-0.70	2.10	0.40	4.70	12.90	20.50	0.60	1.60	0.50	3.60	12.70	20.60	1.70	0.30	0.20	0.80
$V_{s\Phi}$	**13.14**	**20.40**	**3.77**	**0.13**	**0.10**	**0.59**	**13.40**	**20.46**	**3.16**	**1.62**	**0.46**	**3.64**	**13.32**	**20.40**	**3.44**	**1.52**	**0.44**	**3.76**	**13.68**	**20.52**	**3.36**	**0.30**	**0.14**	**0.62**
$\sigma_{sV\Phi}$	**1.42**	**0.67**	**2.71**				**1.60**	**0.72**	**3.07**				**1.79**	**0.75**	**2.84**				**2.58**	**0.61**	**2.94**			
97-01	15.00	20.86	2.06	0.10	0.07	0.43	15.70	20.90	0.60	0.90	0.30	2.40	15.60	20.90	1.10	1.00	0.30	2.30	15.60	21.00	1.70	0.50	0.10	0.50
98-02	11.35	20.21	7.56	0.09	0.07	0.43	11.30	20.20	7.80	1.00	0.40	2.00	11.30	20.10	7.90	1.10	0.40	2.20	11.00	20.50	7.50	0.50	0.10	1.00
99-03	12.56	20.13	4.83	0.10	0.07	0.43	12.90	20.00	4.00	1.40	0.40	2.90	13.20	20.00	2.70	1.50	0.40	2.50	13.70	20.20	1.70	0.20	0.10	0.70
00-04	13.72	19.99	1.03	0.09	0.06	0.38	13.70	19.90	1.30	1.30	0.30	3.00	13.70	19.90	1.10	1.10	0.30	2.60	12.70	19.70	1.20	0.20	0.00	0.70
$V_{s\Phi}$	**13.16**	**20.30**	**3.87**	**0.10**	**0.07**	**0.42**	**13.40**	**20.25**	**3.43**	**1.15**	**0.35**	**2.58**	**13.45**	**20.23**	**3.20**	**1.18**	**0.35**	**2.40**	**13.25**	**20.35**	**3.03**	**0.35**	**0.08**	**0.73**
$\sigma_{sV\Phi}$	**1.35**	**0.33**	**2.54**				**1.58**	**0.39**	**2.83**				**1.53**	**0.40**	**2.79**				**1.67**	**0.47**	**2.59**			
97-02	12.92	20.52	5.10	0.07	0.05	0.33	13.60	20.60	3.50	1.00	0.20	2.30	13.70	20.60	3.50	1.20	0.30	2.70	13.30	20.70	3.40	0.30	0.10	0.90
98-03	12.57	20.28	5.79	0.07	0.05	0.33	12.80	20.20	5.20	0.90	0.30	2.00	13.30	20.20	4.80	0.80	0.30	2.00	13.50	20.40	4.80	0.20	0.10	0.60
99-04	13.25	20.25	1.86	0.07	0.05	0.29	13.10	20.20	2.20	1.00	0.30	2.10	13.30	20.10	1.80	0.80	0.30	1.60	13.00	20.30	2.00	0.10	0.10	0.30
$V_{s\Phi}$	**12.91**	**20.35**	**4.25**	**0.07**	**0.05**	**0.32**	**13.17**	**20.33**	**3.63**	**0.97**	**0.27**	**2.13**	**13.43**	**20.30**	**3.37**	**0.93**	**0.30**	**2.10**	**13.27**	**20.47**	**3.40**	**0.20**	**0.10**	**0.60**
$\sigma_{sV\Phi}$	**0.28**	**0.12**	**1.71**				**0.33**	**0.19**	**1.23**				**0.19**	**0.22**	**1.23**				**0.21**	**0.17**	**1.14**			
97-03	13.50	20.48	4.15	0.06	0.04	0.26	14.10	20.50	2.80	0.80	0.20	1.70	14.30	20.50	2.40	0.80	0.20	1.70	13.50	20.50	3.10	0.20	0.10	0.40
98-04	13.09	20.32	3.22	0.05	0.04	0.23	13.00	20.30	3.50	0.70	0.20	1.60	13.30	20.20	2.70	0.50	0.20	1.20	13.10	20.40	3.40	0.10	0.10	0.40
$V_{s\Phi}$	**13.30**	**20.40**	**3.69**	**0.06**	**0.04**	**0.25**	**13.55**	**20.40**	**3.15**	**0.75**	**0.20**	**1.65**	**13.80**	**20.35**	**2.55**	**0.65**	**0.20**	**1.45**	**13.30**	**20.45**	**3.25**	**0.15**	**0.10**	**0.40**
$\sigma_{sV\Phi}$	**0.20**	**0.08**	**0.46**				**0.55**	**0.10**	**0.35**				**0.50**	**0.15**	**0.15**				**0.20**	**0.05**	**0.15**			
97-04	13.63	20.43	2.55	0.04	0.03	0.19	14.00	20.50	2.00	0.60	0.10	1.40	14.10	20.50	1.80	0.60	0.20	1.20	13.50	20.50	1.90	0.10	0.10	0.30
$V_{s\Phi}$	**13.44**	**20.42**	**3.19**	**0.16**	**0.12**	**0.72**	**13.70**	**20.45**	**2.62**	**1.46**	**0.50**	**3.71**	**13.74**	**20.42**	**2.51**	**1.35**	**0.48**	**3.61**	**13.72**	**20.59**	**2.87**	**0.32**	**0.12**	**0.96**
$\sigma_{sV\Phi}$	**2.34**	**0.63**	**4.55**				**2.56**	**0.67**	**4.67**				**2.51**	**0.70**	**4.60**				**2.84**	**0.78**	**5.05**			

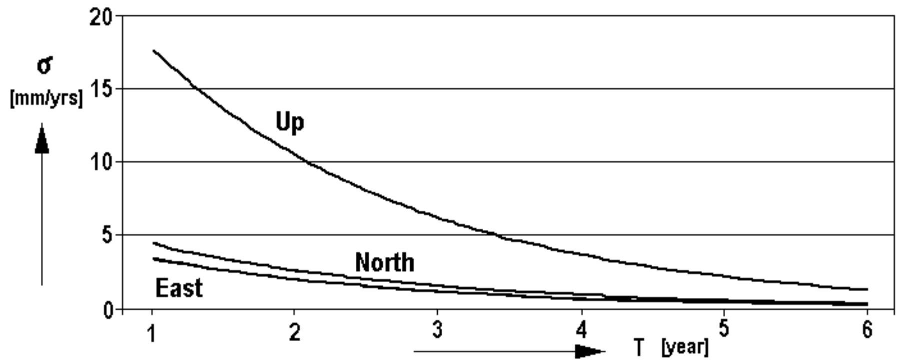

Fig. 7 The relationships of σ_{sVN} , σ_{sVE} and σ_{sVUp} standard deviations of the individual components of the site movement velocities to the T observation period.

Table 7 Coefficients of the equation (2) obtained for four tested approximations: the BERNESE GPS software (B), Least Squares (LS), M–Estimation (M), and Least Median of Squares (LMS) methods.

Method	Velocity component	*a*	*b*	Regression coefficient
BERNESE v. 4.2	$V_{N(B)}$	7.3451	0.5175	0.9977
	$V_{E(B)}$	5.8813	0.5423	0.9991
	$V_{Up(B)}$	29.649	0.5223	0.9970
Least Square (LS)	$V_{N(LS)}$	7.7473	0.5202	0.9974
	$V_{E(LS)}$	6.1716	0.5333	0.9974
	$V_{Up(LS)}$	30.612	0.5308	0.9987
M-estimation (M)	$V_{N(M)}$	7.7674	0.5195	0.9972
	$V_{E(M)}$	5.9646	0.5351	0.9988
	$V_{Up(M)}$	29.818	0.5338	0.9977
Least Median (LMS)	$V_{N(LMS)}$	8.2668	0.5293	0.9967
	$V_{E(LMS)}$	6.3544	0.5420	0.9984
	$V_{Up(LMS)}$	30.232	0.5232	0.9958

Table 8 Coefficients of the relation (3) achieved by averaging the *a* and *b* coefficients of four linear approximations; the BERNESE GPS software v. 4.2 (B), Least Squares (LS), M–Estimation (M), and Least Median of Squares (LMS) methods

$\sigma_{sV\Phi}$	$\overline{a}$	$\overline{b}$	Regression coefficient
σ_{sVN}	7.782 ± 0.327	0.522 ± 0.005	0.997 ± 0.027
σ_{sVE}	6.093 ± 0.184	0.538 ± 0.004	0.998 ± 0.036
σ_{sVUp}	30.078 ± 0.374	0.528 ± 0.005	0.997 ± 0.046

Summarizing this statistical analysis, we conclude that no pronounced differences were found among $V_{s\Phi}$ values evaluated by all four methods. Generally, site velocities obtained approximately for four and more annual epoch solutions display almost identical movement trends.

6. RELIABILITY OF GPS DATA

Reliability of any value determined statistically from a set of experimental data is often evaluated by its standard deviation. In our case, for the assessment of the reliability of individual $V_{s\Phi}$ site movements the following probabilistic criterion

Table 9 Average and maximum σ_{sV}/V_s rates in [%] relating to geodetic components and amount of the annual epoch solutions

Annual epoch solutions	$(\sigma_{sVN(B)}/V_{sN(B)})*100$		$(\sigma_{sVE(B)}/V_{sE(B)})*100$		$(\sigma_{sVUp(B)}/V_{sUp(B)})*100$	
	Mean	Max.	Mean	Max.	Mean	Max.
2	34.17±15.02	49.187	15.94±5.83	21.773	3000±7682	10682
3	18.30±7.66	25.956	**9.78±4.40**	14.175	1649±3620	5269
4	**10.76±5.01**	15.774	**5.90±3.28**	**9.184**	113±683	796
5	**6.28±4.09**	**10.369**	**3.09±2.10**	**5.187**	107±346	453
6	**4.40±3.05**	**7.444**	**1.95±1.43**	**3.377**	90±253	343
7	**2.27±1.74**	**4.012**	**1.10±0.84**	**1.931**	31±112	143

$$\sigma_{sV}/V_s \le N/100 \tag{4}$$

was introduced, where $\sigma_{sV\Phi}$ is the standard deviation of the site movement velocity $V_{s\Phi}$ determined for one site from annual epoch solutions of the T-year set. The coefficient N [%] appoints a probability interval thresholds inside of them all $V_{s\Phi}$ movements should be found in other future measurements. By this way the σ_{sV} deviation and coefficient N establish reliability measures for recent site movement V_s assessments.

The reliabilities of all $V_{s\Phi}$ site movements presented above were evaluated with three probability thresholds, 10 %, 5 % and 2 %, respectively. It means, if the probability threshold $N = 10$ % then $\sigma_{sV} \le 0.1*V_s$ and, similarly, if $N = 5$% then $\sigma_{sV} \le 0.05*V_s$ and if $N = 2$ % then $\sigma_{sV} \le 0.02*V_s$.

Table 8 summarizes a decrease of the σ_{sV}/V_s rates relating to geodetic components with respect to amount of the annual epoch solutions.

The σ_{sV}/V_s rates in Table 9 allow possible category thresholds of reliable site movements to be established. Our experiences with the GPS data applications in geodynamic tasks lead us to introduce the following probability thresholds to assess the reliability of the data:

- probable site velocity – if $N \le 10$ % ,
- possible site velocity – if $N \le 5$ % , and
- credible site velocity – if $N \le 2$ % .

The rates presented in Table 8 show how many GPS annual epoch measurements have to be carried out to obtain site movements that are able to be applied to geodynamic tasks.

The site horizontal movements take on probable and possible values in the north component in 4 or 5 annual epochs and in the east component in 3 or 4 annual epochs, respectively. In Table 4 the $V_{s\Phi(B)}$ and $\sigma_{sV\Phi(B)}$ mean values determined from GPS data sets of four and more epoch solutions show that they can be already taken as credible ones. When more such solutions exist for one site then the final average values and their standard deviations (in Table 4 marked by symbols $V_{s\Phi(B)}\approx$ and $\sigma_{sV\Phi(B)}\approx$) of the horizontal components reach already the threshold categories of the credible movements and the vertical component is very close to be classified as the probable movement velocity.

Contrary to horizontal movements, the vertical site movements display enormous level of inaccuracy of their determinations. The origin of these great differences is just in the proper nature of geodynamic movements of the tectonic plates. Everybody knows that crustal plates move on the Earth's surface and on the contrary they hardly move in vertical directions. From this viewpoint, one can trace that in majority GPS sites the horizontal movements are ten or more times greater then the vertical ones. Only in several dynamically active areas and/or zones, e.g. the Circum Pacific and the Alps Himalayan earthquake belts, the vertical movements can be a few times smaller then the horizontal ones. This fact explains why a satisfactory level of reliable vertical movements cannot be reached after realization of several epoch measurements.

This general formulation does not pay e.g. for the STRE and SVES sites that display relatively great uplifting trends with respect to other sites; the shift of these observed vertical movements deflect them to the category of probable movements (Fig. 5 and Table 2). Because of the positions of both sites, they are situated closely to the Carpathian neotectonic structures (Fig. 1), the detected uplift trends could signalize an existence of higher vertical movement tendencies rather than any erroneous values.

Besides, it seems that the newly developed InSAR technology, especially its persistant scatter technology (PSI) approach, could improve and precise effectively the vertical velocity movement assessments. The PSI technology is able to deliver additional quite independent evaluations of site vertical movements (Ferretti et al., 2000, 2001; Hanssen, 2004). A few recent results signalize that a comparison of the GPS and PS InSAR interpreted movements could significantly and effectively shorten the time to reach reliable values of the site vertical movements.

7. RECOMMENDATIONS AND CONCLUSIONS

The BERNESE GPS software v. 4.2., module ADDNEQ, and other linear approximations of the Least Square, the M-estimation and the Least Median of Square methods were applied to GPS data of eight annual epoch solutions (1997-2004) on the EAST SUDETEN geodynamic network, the Bohemian Massif, to obtain reliable approximations of time series of network site positions and to exclude and/or mitigate outlier effects. Statistical analyses of site velocity movements allowed three probability thresholds for site movements to be defined: (a) probable, (b) possible and (c) credible movements. To reach similar GPS data reliable levels, it is recommended, to follow the way of epoch measurements and data processing described above.

It was found that the probable / credible site horizontal movements can be obtained for the north component in 4 or 5 annual epochs and for the east component in 3 or 4 annual epochs, respectively. When more than 4 annual epoch solutions, then $V_{s\Phi}$ mean values can already reach the category of the credible velocity. As to the site vertical movements their values need more annual epoch solutions, probably close to 10 epochs, to reach the category of probable / credible site movements. To shorten this period, it seems to be helpful in future to combine the GPS site vertical movements with the new PSI technology.

The probabilistic thresholds defining reliable site movements brought further important recommendation for the GPS practice. It is evident, if any GPS measurements are planned on regional networks aimed to geodynamic studies then it should be taken into account a fact that whole period of these planned measurements would not be less than six years. This conclusion is imperative for many recent project proposals planned for geodynamic and any geodetic interpretations.

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APPENDIX: TERMS AND ABBREVIATIONS

Geodetic coordinates determine a position of the point on the Earth surface using the longitude and latitude in the sense of the ellipsoidal coordinates and the height above the ellipsoid in the sense of normal line to the ellipsoid. The positive *geodetic components* of the longitude head to the East (E), the latitude to the North (N) and the height above the ellipsoid (Up).

Φ – common symbol for all geodetic coordinates together, i.e. N, E and Up, respectively,

$S_{\Phi(B)}$ – common symbol for site positions given in the geodetic coordinates estimated by the BERNESE ADDNEQ module.

$S_{N(B)}$, $S_{E(B)}$, $S_{Up(B)}$ – three geodetic coordinates of a site position estimated by the BERNESE ADDNEQ module.

Geocentric Cartesian coordinates determine a position of the point on the Earth surface using orthogonal coordinates that origin is situated in the Earth mass centre. The positive *geocentric components* of the X coordinate head to the Greenwich meridian (0ºE), the Y coordinate to the 90ºE meridian and the Z coordinates to the northern pole (90ºN).

Θ – common symbol for all geocentric coordinates together, i.e. X, Y and Z, respectively,

$S_{\Theta(B)}$ – common symbol for site positions given in the geocentric coordinates estimated by the BERNESE ADDNEQ module.

$S_{X(B)}$, $S_{Y(B)}$, $S_{Z(B)}$ – free geocentric coordinates of a site position estimated by the BERNESE ADDNEQ module.

Site movement velocity determines a rate of speed how quickly the site moves in time. In our study it is expressed in millimetres per year usually in the geodetic coordinate system.

$V_{N(B)}$, $V_{E(B)}$, $V_{Up(B)}$ – movement velocities determined by the BERNESE ADDNEQ module in the geodetic coordinates,

$V_{N(LS)}$, $V_{E(LS)}$, $V_{Up(LS)}$ – movement velocities determined by the Least Squares regression, independently for each coordinate, in the geodetic coordinates,

$V_{N(M)}$, $V_{E(M)}$, $V_{Up(M)}$ – movement velocities determined by the robust M-estimation method, independently for each coordinate, in the geodetic coordinates,

$V_{N(LMS)}$, $V_{E(LMS)}$, $V_{Up(LMS)}$ – movement velocities determined by the robust Least Median of Squares method, independently for each coordinate in the geodetic coordinates,

$V_{\Phi(B)}$ – common symbol for $V_{N(B)}$, $V_{E(B)}$ and $V_{Up(B)}$,

$V_{\Phi(LS)}$ – common symbol for $V_{N(LS)}$, $V_{E(LS)}$ and $V_{Up(LS)}$,

$V_{\Phi(M)}$ – common symbol for $V_{N(M)}$, $V_{E(M)}$ and $V_{Up(M)}$,

$V_{\Phi(LMS)}$ – common symbol for $V_{N(LMS)}$, $V_{E(LMS)}$ and $V_{Up(LMS)}$,

V_{Φ} – common symbol for $V_{\Phi(B)}$, $V_{\Phi(LS)}$, $V_{\Phi(M)}$ and $V_{\Phi(LMS)}$.

$V_{sN(B)}$, $V_{sE(B)}$, $V_{sUp(B)}$ – site movement velocities determined in the geodetic coordinates by the Bernese ADDNEQ module from all combinations of GPS data sets observed on a certain site,

$V_{sN(LS)}$, $V_{sE(LS)}$, $V_{sUp(LS)}$ – site movement velocities determined in the geodetic coordinates by the Least Squares regression from all combinations of GPS data sets observed on a certain site,

$V_{sN(M)}$, $V_{sE(M)}$, $V_{sUp(M)}$ – site movement velocities determined in the geodetic coordinates by the robust M-estimation method from all combinations of GPS data sets observed on a certain site,

$V_{sN(LMS)}$, $V_{sE(LMS)}$, $V_{sUp(LMS)}$ – site movement velocities determined in the geodetic coordinates by the robust Least Median of Squares method from all combinations of GPS data sets observed on a certain site,

$V_{s\Phi(B)}$ – common symbol for $V_{sN(B)}$, $V_{sE(B)}$ and $V_{sUp(B)}$

$V_{s\Phi(LS)}$ – common symbol for $V_{sN(LS)}$, $V_{sE(LS)}$ and $V_{sUp(LS)}$

$V_{s\Phi(M)}$ – common symbol for $V_{sN(M)}$, $V_{sE(M)}$ and $V_{sUp(M)}$

$V_{s\Phi(LMS)}$ – common symbol for $V_{sN(LMS)}$, $V_{sE(LMS)}$ and $V_{sUp(LMS)}$

$V_{s\Phi}$ – common symbol for $V_{s\Phi(B)}$, $V_{s\Phi(LS)}$, $V_{s\Phi(M)}$ and $V_{s\Phi(LMS)}$

$V_{s\Phi(B)}{\approx}$ – mean site movement velocity determined by the BERNESE ADDNEQ solution for the geodetic components with respect to the probability thresholds defined for the probable site movement values

Standard deviation σ (*syn.* root-mean-square deviation) *for a random variable* is the positive square root of the variance representing the 2nd moment of the variable about its mean (the 1st moment). Then σ can be understood as a measure that characterizes a *width* or *variability* around the mean of the variable distribution.

$\sigma_{N(B)}$, $\sigma_{E(B)}$, $\sigma_{Up(B)}$ – σ of the site position determined by the BERNESE ADDNEQ module and assessed in geodetic coordinates,

$\sigma_{\Phi(B)}$ – common symbol for $\sigma_{N(B)}$, $\sigma_{E(B)}$ and $\sigma_{Up(B)}$,

$\sigma_{VN(B)}$, $\sigma_{VE(B)}$, $\sigma_{VUp(B)}$ – σ of the movement velocities determined by the BERNESE ADDNEQ module and assessed in the geodetic coordinates,

$\sigma_{VN(LS)}$, $\sigma_{VE(LS)}$, $\sigma_{VUp(LS)}$ – σ of movement velocities determined by the Least Squares method and assessed in the geodetic components,

$\sigma_{VN(M)}$, $\sigma_{VE(M)}$, $\sigma_{VUp(M)}$ – σ of movement velocities determined by the robust M-estimation method and assessed in the geodetic coordinates,

$\sigma_{VN(LMS)}$, $\sigma_{VE(LMS)}$, $\sigma_{VUp(LMS)}$ – σ of movement velocities determined by the robust Least Median of Squares method and assessed in the geodetic coordinates,

$\sigma_{V\Phi(B)}$ – common symbol for $\sigma_{VN(B)}$, $\sigma_{VE(B)}$ and $\sigma_{VUp(B)}$

$\sigma_{V\Phi(LS)}$ – common symbol for $\sigma_{VN(LS)}$, $\sigma_{VE(LS)}$ and $\sigma_{VUp(LS)}$,

$\sigma_{V\Phi(M)}$ – common symbol for $\sigma_{VN(M)}$, $\sigma_{VE(M)}$ and $\sigma_{VUp(M)}$,

$\sigma_{V\Phi(LMS)}$ – common symbol for $\sigma_{VN(LMS)}$, $\sigma_{VE(LMS)}$ and $\sigma_{VUp(LMS)}$,

$\sigma_{V\Phi}$ – common symbol for $\sigma_{V\Phi(B)}$, $\sigma_{V\Phi(LS)}$, $\sigma_{V\Phi(M)}$ and $\sigma_{V\Phi(LMS)}$,

$\sigma_{sN(B)}$, $\sigma_{sE(B)}$, $\sigma_{sUp(B)}$ – σ of site movement velocities determined by the BERNESE ADDNEQ solution for the geodetic components,

$\sigma_{sN(LS)}$, $\sigma_{sE(LS)}$, $\sigma_{sUp(LS)}$ – σ of site movement velocities determined by the Least Squares estimation for the geodetic components,

$\sigma_{sN(M)}$, $\sigma_{sE(M)}$, $\sigma_{sUp(M)}$ – σ of site movement velocities determined by the robust M-estimation for the geodetic components,

$\sigma_{sN(LMS)}$, $\sigma_{sE(LMS)}$, $\sigma_{sUp(LMS)}$ – σ of site velocities determined by the robust Least Median of Squares estimation for the geodetic components.

$\sigma_{sVN(B)}$, $\sigma_{sVE(B)}$, $\sigma_{sVUp(B)}$ – σ of site movement velocities determined by the BERNESE ADDNEQ solution in the geodetic coordinates from all combinations of GPS data sets observed for a certain site,

$\sigma_{sVN(LS)}$, $\sigma_{sVE(LS)}$, $\sigma_{sVUp(LS)}$ – σ of site movement velocities determined by the Least Squares estimation in the geodetic coordinates from all combinations of GPS data sets observed for a certain site,

$\sigma_{sVN(M)}$, $\sigma_{sVE(M)}$, $\sigma_{sVUp(M)}$ – σ of site movement velocities determined by the robust M-estimation in the geodetic coordinates from all combinations of GPS data sets observed for a certain site,

$\sigma_{sVN(LMS)}$, $\sigma_{sVE(LMS)}$, $\sigma_{sVUp(LMS)}$ – σ of site movement velocities by the robust Least Median of Squares estimation in the geodetic coordinates from all combinations of GPS data sets observed for a certain site,

$\sigma_{sV\Phi(B)}$ – common symbol for $\sigma_{sVN(B)}$, $\sigma_{sVE(B)}$ and $\sigma_{sVUp(B)}$,

$\sigma_{sV\Phi(LS)}$ – common symbol for $\sigma_{sVN(LS)}$, $\sigma_{sVE(LS)}$ and $\sigma_{sVUp(LS)}$,

$\sigma_{sV\Phi(M)}$ – common symbol for $\sigma_{sVN(M)}$, $\sigma_{sVE(M)}$ and $\sigma_{sVUp(M)}$,

$\sigma_{sV\Phi(LMS)}$ – common symbol for $\sigma_{sVN(LMS)}$, $\sigma_{sVE(LMS)}$ and $\sigma_{sVUp(LMS)}$,

$\sigma_{sV\Phi}$ – common symbol for $\sigma_{sV\Phi(B)}$, $\sigma_{sV\Phi(LS)}$, $\sigma_{sV\Phi(M)}$ and $\sigma_{sV\Phi(LMS)}$.

$\sigma_{sV\Phi(B)}{\approx}$ – mean σ determined by the BERNESE ADDNEQ solution with respect to the probability thresholds defined for the probable site movement values.

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