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CERGOP GPS DATA PROCESSING AND ANALYSIS OF THE RESULTS RELATED TO THE REGION OF THE BALKANS

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1. Introduction

- **The main objective of this paper is to study and analyze the geodynamic behavior of GPS stations of the CEGRN subnetwork (Fig. 1) covering Balkan Peninsula (BP'CEGRN).**

- **For the purpose of this study data from three GPS CEGRN measurement campaigns CEGRN97, CEGRN03 and CEGRN05 which include the Balkan Peninsula stations (permanent and epoch) have been involved.**

- **Seven IGS sites have been used as reference.**

- **The ITRF2000 station coordinate and velocity estimations obtained have been compared and analyzed. The velocity estimations have been also compared with those ones obtained from NUVEL1A-NNR velocity model and with EPN estimated velocities for the participated EPN stations.**

Fig.1. Balkan Peninsula CEGRN subnetwork stations

2. Data processing and results

- **The results from data processing of the BP'CEGRN03 campaign and BP'CEGRN97 campaign reported and published earlier are used here. BP'CEGRN05 data have been newly processed for this.**

- **For obtaining the station velocity estimations the following combined campaign solutions – BP'CEGRN97/BP"CEGRN03, BP'CEGRN97/BP'CEGRN05 and BP'CEGRN03/BP'CEGRN05 have been accomplished.**

- **The main results from processing of the individual campaigns are presented below.**

Balkan Peninsula CEGRN97campaign

- **The ITRF2000 coordinates at the epoch of observation 1997.44 for the 13 participated stations have been estimated.**

- **The values of the standard deviations (in North, East and Up) for each station after comparison of the coordinates are presented in the figure 2.**

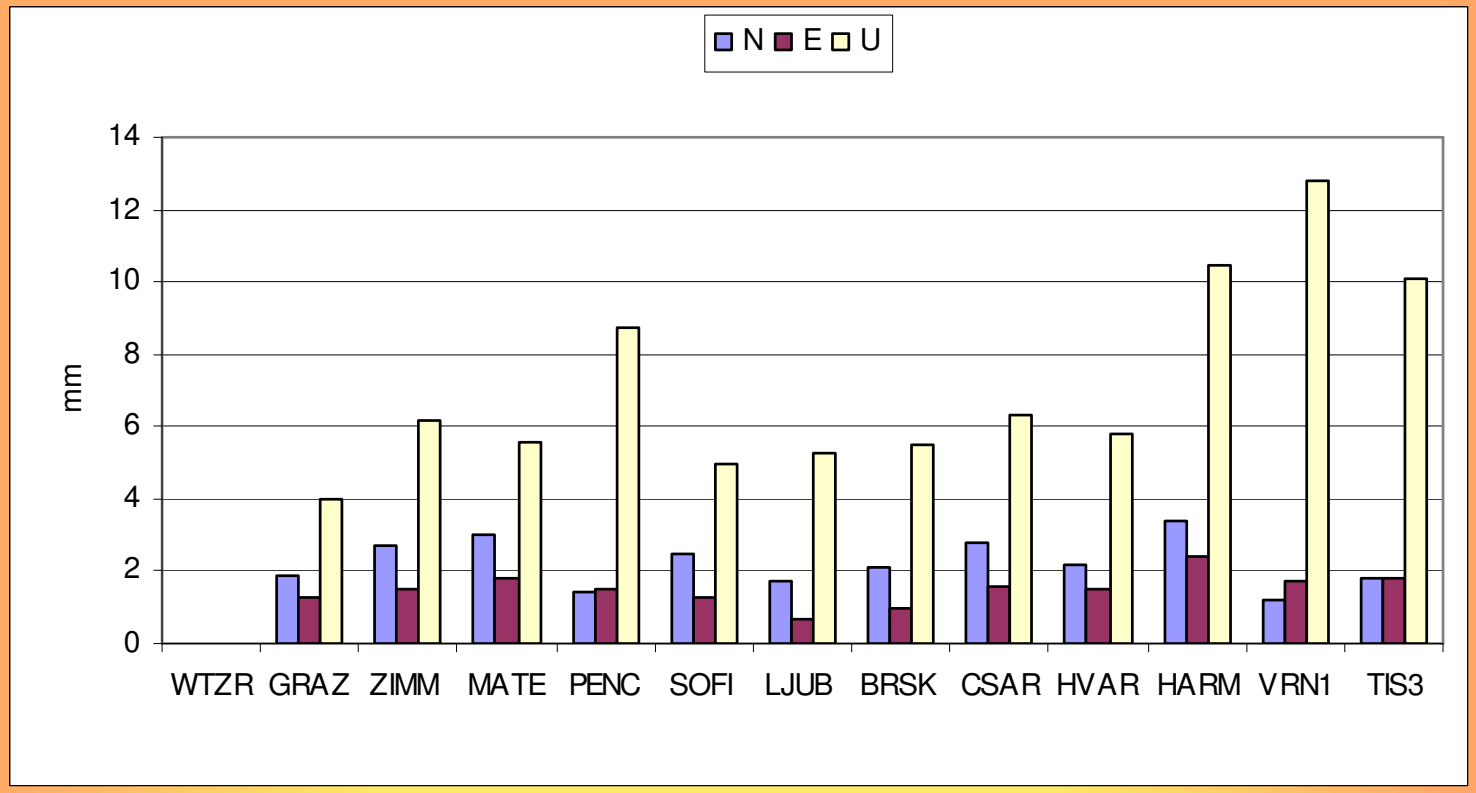

Fig 2. RMS of comparison of BP'CEGRN97 daily solutions

- **The results show a good consistence. The maximum deviation of amount 12.8 mm in Up component is for station VRN1.**

Balkan Peninsula CEGRN03 campaign

- **The ITRF2000 coordinates at the epoch of observation 2003.46 for the participated 29 stations have been estimated.**

- **The main results from comparison of the six session solutions are presented in the figure 3.**

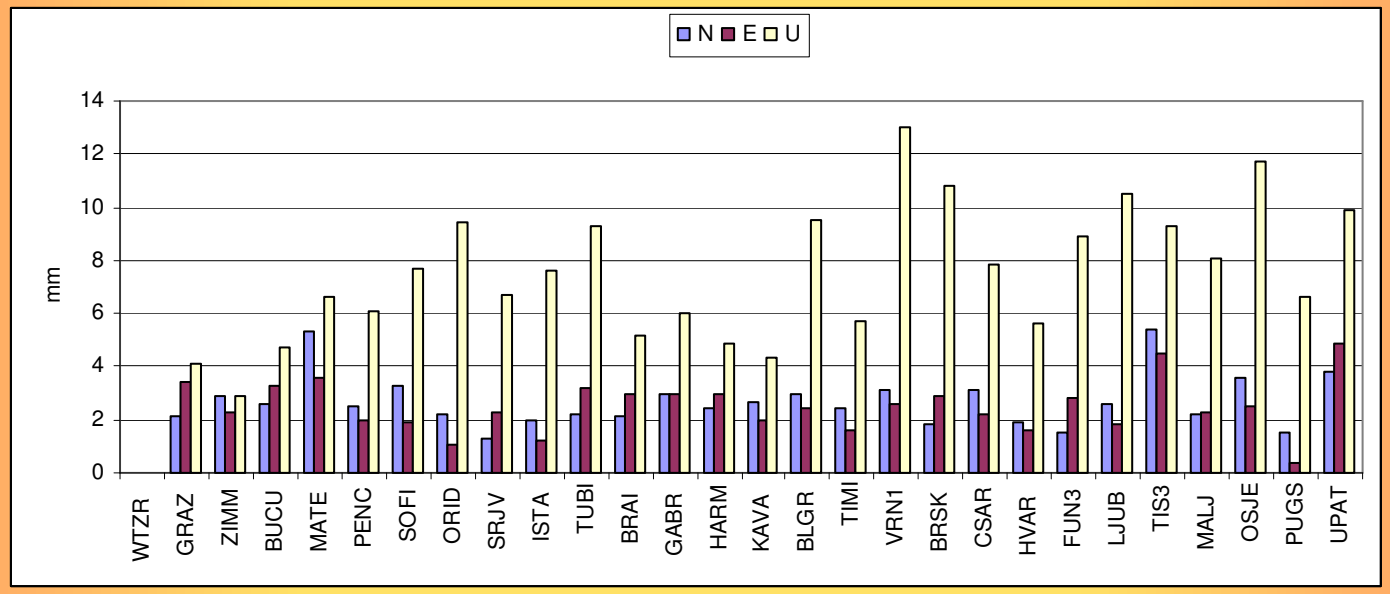

Fig. 3. RMS of comparison of BP'CEGRN03 session solutions

- **The largest deviation of amount 13.0 mm in Up component is again for station VRN1. The rms's in North and East components vary between 1.5 mm and 5.6 mm.**

Balkan Peninsula CEGRN05 campaign

- **The ITRF2000 coordinates at the epoch of observation 2005.47 for the participated 35 stations have been estimated.**
- **The results from the comparison of the six session solutions presenting the quality of the network measurements are given in the figure 4.**

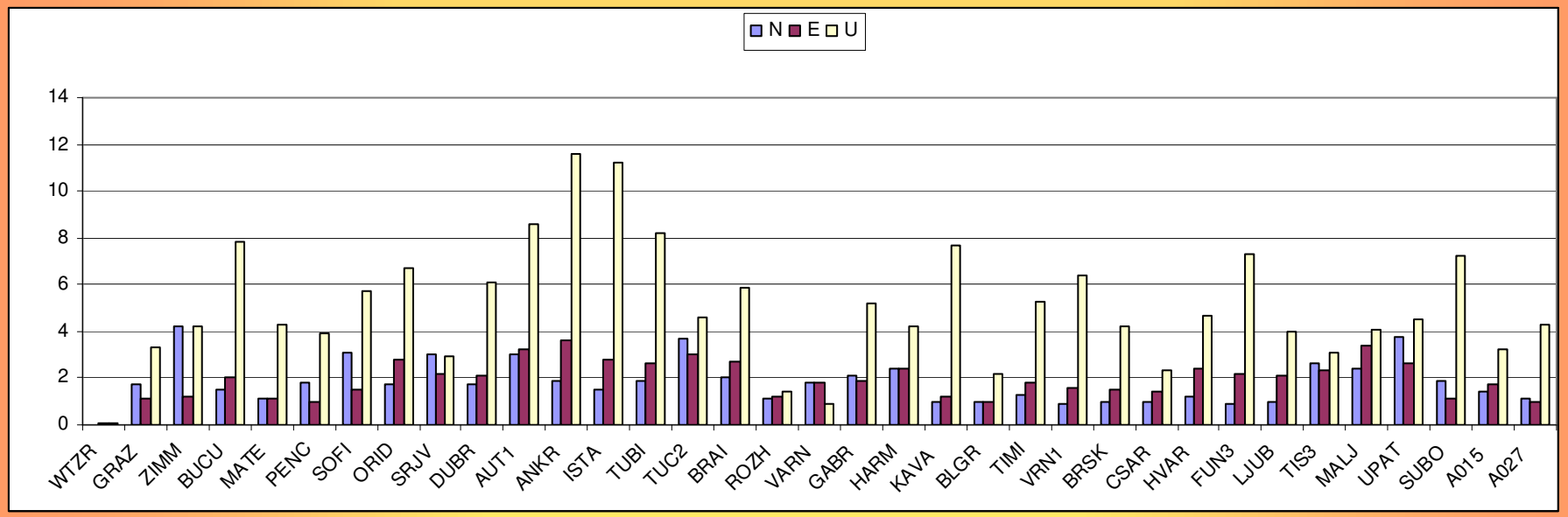

Fig. 4. RMS of comparison of BP'CEGRN05 session solutions

- **The values of deviations in North and East components vary between 1-4 mm and for Up component between 3-8 mm. Only for stations ANKR and ISTA rms's are about 12 mm. These results show a very good consistence.**

3. Comparison and analysis of the results from combined solutions

- **Combined solution of BP'CEGRN97 and BP'CEGRN03 have been already done and published and an improved solution is presented here. Combinations of normal equations from BP'CEGRN97 and BP'CEGRN05, and BP'CEGRN03 and BP'CEGRN05 campaign solutions have been processed using Addneq of Bernese Software, Version 4.2.**

- **Firstly an evaluation of participated stations has been done in two steps:**
  1) evaluation of estimated coordinates only for reference IGS stations and
  2) evaluation of all participated station coordinates.

- **Estimated velocities from different combined solutions have been compared and analyzed. Comparison with NUVEL1A-NNR calculated velocities and EPN estimated velocities has been done as well.**

3.1. Comparison and analysis of the results for participated IGS permanent stations used as reference

BP'CEGRN97 - BP'CEGRN03

- **7-parameters Helmert transformations have been applied for the coordinates of the IGS reference stations obtained from combined BP'CEGRN97 – BP'CEGRN03 solution and ITRF2000 official published coordinates at the epochs 1997.44 and 2003.46 respectively.**

Table 1. Residuals from Helmert transformations between sets of estimated BP'CEGRN97–BP'CEGRN03 and official ITRF2000 published coordinates of IGS stations for the respective observation epochs with station MATE marked

No	Site Name	Residuals in mm							
		BP'CEGRN97-BP'CEGRN03/ ITRF2000, epoch 1997.44				BP'CEGRN97-BP'CEGRN03/ ITRF2000, epoch 2003.46			
		N	E	U		N	E	U	
1	GRAZ 11001M002	1.9	0.5	-1.6		-3.0	-1.0	3.8	
2	MATE 12734M008	12.9	4.4	0.0	M	18.0	-4.1	-0.8	M
3	PENC 11206M006	1.9	-0.4	6.1		-0.2	0.8	-2.1	
4	SOFI 11100M002	-2.0	-0.1	-1.8		2.0	-0.2	-0.3	
5	WTZR 14201M010	-1.4	-1.5	-5.5		0.3	2.1	-0.2	
6	ZIMM 14001M004	-0.3	1.5	2.7		0.9	-1.8	-1.2	
	RMS/Component	1.8	1.1	4.5		1.9	1.5	2.3	
	RMS of transformation	3.5				2.3			

- **High values in North component for stations MATE and SOFI occurred in both cases. It is not quite clear if the problem with this station happened in 1997 or in 2003. After marking station MATE the residuals become smaller.**

BP'CEGRN97 - BP'CEGRN05

- **The residuals from 7-parameters Helmert transformations between sets of coordinates from combined BP'CEGRN97 - BP'CEGRN05 solution and ITRF2000 official published coordinates at the observation epochs 1997.44 and 2005.47 respectively have been obtained.**

Table 2. Residuals from Helmert transformations between sets of estimated BP'CEGRN97 – BP'CEGRN05 and official ITRF2000 published coordinates of IGS stations for the respective observation epochs with station MATE marked

No	Site Name	Residuals in mm							
		BP'CEGRN97-BP'CEGRN05 / ITRF2000, epoch 1997.44				BP'CEGRN97-BP'CEGRN05 / ITRF2000, epoch 2005.47			
		N	E	U		N	E	U	
1	GRAZ 11001M002	3.1	0.7	-2.8		-1.8	-0.7	3.5	
2	MATE 12734M008	19.7	5.8	0.3	M	-22.1	-1.8	1.7	M
3	PENC 11206M006	2.2	-1.1	6.8		-3.4	3.0	1.0	
4	SOFI 11100M002	-3.1	0.2	-1.7		4.0	-1.1	-1.2	
5	WTZR 14201M010	-1.5	-2.3	-5.4		1.1	2.3	-3.5	
6	ZIMM 14001M004	-0.7	2.5	3.1		0.2	-3.5	0.1	
	RMS/Component	2.6	1.8	4.9		2.8	2.7	2.6	
	RMS of transformation	4.1				3.3			

- **As above the problem in both campaigns is again with station MATE.**

BP'CEGRN03 - BP'CEGRN05

- **The residuals from 7-parameters Helmert transformations between the sets of coordinates from combined BP'CEGRN03 - BP'CEGRN05 solution and ITRF2000 official published coordinates at the observation epochs 2003.46 and 2005.47 respectively are presented in table 3.**

Table 3. Residuals from Helmert transformations between sets of estimated BP'CEGRN03 – BP'CEGRN05 and official ITRF2000 published coordinates of IGS stations for the respective observation epochs with station BUCU marked

No	Site Name	Residuals in mm							
		BP'CEGRN03-BP'CEGRN05/ ITRF2000, epoch 2003.46				BP'CEGRN03-BP'CEGRN05/ ITRF2000, epoch 2005.47			
		N	E	U		N	E	U	
1	BUCU 11401M001	-14.9	29.6	23.8	M	5.9	-18.8	-33.2	M
2	GRAZ 11001M002	-0.1	-0.1	1.3		-1.3	-0.2	0.5	
3	MATE 12734M008	-3.5	-0.8	0.0		3.4	-1.4	-0.6	
4	PENC 11206M006	0.6	-0.3	-0.7		3.3	-2.1	-3.5	
5	SOFI 11100M002	2.5	-0.7	-0.1		-3.8	3.0	1.6	
6	WTZR 14201M010	0.1	1.1	-0.1		-1.1	-0.5	2.8	
7	ZIMM 14001M004	0.4	0.9	-0.4		-0.4	1.2	-0.8	
	RMS/Component	1.9	0.8	0.7		2.8	1.8	2.2	
	RMS of transformation	1.5				2.7			

- **The values in North and Up components for station BUCU deviate considerably for both campaigns.**

- **Analyzing all above presented results it can be concluded that there was a problem with station MATE occurred most probably in 1997. Station BUCU is problematic in 2003 and in 2005 as well.**

- **To study this problem further a new comparison has been done. Using the EPN estimated velocities for BUCU instead of the ITRF2000 official published velocities new reference coordinates have been calculated for epochs 2003.46 and 2005.47.**

- **The same comparisons have been accomplished but using the new calculated reference coordinates of BUCU. The residuals of this station have been considerably improved (table 4).**

Table 4. Residuals from Helmert transformations between sets of estimated BP'CEGRN03 – BP'CEGRN05 and official ITRF2000 published coordinates of IGS stations for the respective observation epochs using EPN estimated velocity for BUCU

No	Site Name	Residuals in mm							
		BP'CEGRN03-BP'CEGRN05/ ITRF2000, epoch 2003.46				BP'CEGRN03-BP'CEGRN05/ ITRF2000, epoch 2005.47			
		N	E	U		N	E	U	
1	BUCU 11401M001	-6.7	9.5	15.1		-3.6	10.5	11.2	
2	GRAZ 11001M002	0.5	-1.3	-4.2		1.2	-1.3	-2.7	
3	MATE 12734M008	7.6	0.6	0.3		0.4	-0.2	0.9	
4	PENC 11206M006	0.1	-2.9	-7.4		3.6	1.4	5.6	
5	SOFI 11100M002	2.0	-3.2	-10.1		7.0	-7.6	-9.2	
6	WTZR 14201M010	-1.5	-2.6	-1.2		-0.7	-0.3	-3.8	
7	ZIMM 14001M004	-2.0	-0.1	7.5		-0.7	0.1	6.1	
	RMS/Component	4.4	4.4	8.7		3.6	5.4	6.8	
	RMS of transformation	7.0				6.1			

3.2. Comparison and analysis of the results for non-reference stations

- In the second step an evaluation of non-reference stations have been done.
- For this purpose comparisons between sets of estimated coordinates from combined and individual final campaign solutions have been accomplished applying 7-parameters Helmert transformation – tables 5, 6, 7.

Table 5. Residuals from Helmert transformations between sets of estimated coordinates from combined BP'CEGRN97 - BP'CEGRN03 solution and individual campaign solutions

No	Site Name	Residuals in mm							
		BP'CEGRN97-BP'CEGRN03/ BP'CEGRN97				BP'CEGRN97-BP'CEGRN03/ BP'CEGRN03			
		N	E	U		N	E	U	
1	GRAZ 11001M002	2.3	1.9	-4.4		-2.1	2.8	-7.6	
2	MATE 12734M008	12.9	6.9	-6.1	M	-13.8	-4.5	-11.9	M
3	PENC 11206M006	-2.0	0.4	2.0		-2.4	1.3	12.3	
4	SOFI 11100M002	-0.7	2.0	-1.8		1.1	-1.7	-0.7	
5	WTZR 14201M010	-1.0	-1.1	-4.2		0.7	2.6	-4.3	
6	ZIMM 14001M004	-4.3	0.8	-1.6		2.5	-3.6	0.6	
7	BRSK	11.0	29.4	-579.9	M	-8.4	-21.8	327.4	M
8	CSAR	4.0	2.7	-2.7		-5.3	-2.1	4.7	
9	HVAR	13.9	12.8	-39.9	M	-12.5	-10.5	2.6	M
10	LJUB	5.4	-4.7	12.4		-7.0	6.3	-17.7	M
11	TIS3	5.3	-4.8	48.2	M	-5.6	4.7	-52.4	M
12	HARM	-1.0	0.5	-3.2		2.3	-0.5	1.2	
13	VRN1	-2.8	-2.5	3.6		3.1	1.3	-6.1	
	RMS/Component	3.2	2.4	5.4		3.0	2.3	6.4	
	RMS of transformation	4.2				4.8			

- **Obviously there is an outlier in the height of BRSK but from the transformations is difficult to say in which year.**
- **The above presented results show that there was an error most likely in the height of station HVAR in 1997.**
- **For stations BRSK and TIS3 it is not clear if the error (suspected wrong heights) occurred in 1997 or in 2003 because it has appeared in transformation results for both years.**
- **The residuals of TIS3 in Up component are in the same order in 1997 and in 2003 and it can be interpreted as an error in the height or as movement.**

BP'CEGRN97 - BP'CEGRN05

Table 6. Residuals from Helmert transformations between sets of estimated coordinates from combined BP'CEGRN97 - BP'CEGRN05 solution and individual campaign solutions

No	Site Name	Residuals in mm							
		BP'CEGRN97-BP'CEGRN05/ BP'CEGRN97				BP'CEGRN97-BP'CEGRN05/ BP'CEGRN05			
		N	E	U		N	E	U	
1	GRAZ 11001M002	4.3	1.2	-2.2		3.4	-2.6	-9.3	
2	MATE 12734M008	21.8	5.7	-0.1	M	-16.1	-4.5	-4.7	M
3	PENC 11206M006	-1.6	-1.7	5.9		-3.8	1.6	2.9	
4	SOFI 11100M002	-1.3	-1.2	3.3		1.5	-0.4	1.6	
5	WTZR 14201M010	-0.6	-2.0	-1.3		-0.2	3.0	0.2	
6	ZIMM 14001M004	-3.0	2.1	2.4		0.4	-1.2	5.3	
7	BRSK	1.2	1.4	-10.6	M	-10.4	-0.6	-1.0	M
8	CSAR	5.1	0.5	-6.5		-4.0	-1.8	-3.1	
9	HVAR	22.6	10.5	-25.9	M	-19.0	-9.4	10.5	M
10	LJUB	9.7	-0.4	-3.6	M	-9.5	1.5	-4.8	M
11	TIS3	4.8	-9.1	13.3	M	-2.2	4.8	-14.8	
12	HARM	-2.9	1.2	-1.6		9.2	-7.0	-4.3	M
13	VRN1	-0.3	-9.8	-19.1	M	2.7	1.4	2.4	
	RMS/Component	3.3	1.6	4.1		3.0	2.0	4.9	
	RMS of transformation	3.6				4.0			

- **Analyzing the results from these comparisons it can be concluded that a problem with the height of station VRN1 occurred in 1997.**
- **Residuals of BRSK are not as high as they are in the previous comparison (table 5) and by this reason it is supposed that an outlier in the height of this station occurred in 2003.**

BP'CEGRN03 - BP'CEGRN05

Table 7. Residuals from Helmert transformations between sets of estimated coordinates from combined BP'CEGRN03 - BP'CEGRN05 solution and individual campaign solutions

No	Site Name	Residuals in mm							
		BP'CEGRN03-BP'CEGRN05/ BP'CEGRN03				BP'CEGRN03-BP'CEGRN0 / BP'CEGRN05			
		N	E	U		N	E	U	
1	BUCU 11401M001	0.8	-1.9	0.3		-0.4	1.3	-4.6	
2	GRAZ 11001M002	-0.2	3.6	-10.1		6.1	0.7	-16.8	M
3	MATE 12734M008	5.2	2.5	-5.2		-1.6	-1.2	-2.7	
4	PENC 11206M006	-2.1	-0.3	17.5	M	-3.9	3.6	1.8	
5	SOFI 11100M002	-3.5	0.3	5.2		-3.1	0.8	2.9	
6	WTZR 14201M010	-0.2	-2.4	-2.9		1.7	2.5	-4.8	
7	ZIMM 14001M004	-0.8	-5.2	3.9		2.7	-0.7	1.7	
8	ISTA 20807M001	1.8	0.6	-0.1		-0.7	-1.2	5.6	
9	TUBI 20806M001	3.3	-2.3	2.3		-2.4	2.1	7.2	
10	SRJV 11801S001	1.1	0.6	2.1		-0.9	0.3	2.9	
11	ORID 15601M001	-1.2	2.4	0.8		2.1	-1.2	-4.9	
12	BRAI	-3.7	-1.4	4.7		3.9	0.3	-8.2	
13	KAVA	-1.4	-2.8	-6.3		2.3	1.7	4.5	
14	BLGR	-0.3	-2.3	-2.8		-0.5	2.8	1.5	
15	TIMI	-4.6	-0.7	-0.2		4.0	1.0	-4.4	
16	VRN1	2.6	-2.8	-22.8	M	-3.0	1.3	7.7	M
17	BRSK	15.0	-40.5	461.5	M	-14.2	35.2	-435.5	M
18	CSAR	-0.8	-0.8	4.8		1.0	1.4	-0.8	
19	HVAR	5.9	0.9	-6.1		-5.7	1.2	-11.9	
20	FUN3	5.8	-5.9	-42.0	M	-6.2	4.7	21.2	M
21	GABR	-1.6	4.2	-0.9		2.1	-4.5	-0.5	
22	HARM	-2.9	5.7	3.2		3.9	-6.2	-3.7	
23	LJUB	0.6	5.5	-18.3	M	-1.4	-3.9	8.6	
24	TIS3	-2.6	-0.4	-48.9	M	2.3	0.2	22.7	M
25	MALJ	2.8	-1.1	11.8		-3.0	0.0	9.7	
	RMS/Component	2.9	2.7	5.4		2.8	2.5	5.7	
	RMS of transformation	4.0				4.1			

- **The results from this comparison confirm the above speculation that an outlier for station BRSK occurred in 2003.**

- **The problem with GRAZ station occurred most probably in 2005 and for other stations it is difficult to determine in which year it happened.**

3.3. Station velocity estimations and analysis

- **The behavior of stations during the period of study is characterized here by the velocity vectors estimated from the combined campaign solutions with Bernese Software, version 4.2.**

- **Station velocity estimations have been obtained with respect to the fixed ITRF2000 coordinates and velocities, epoch 1997.0 of reference IGS stations - WTZR, GRAZ, MATE, ZIMM, SOFI and PENC.**

Table 8. Estimated ITRF2000 station velocities from different combined solutions, calculated NNR-NUVEL1A velocities and EPN velocities

No	STATION NAME	V_X (mm/y)					V_Y (mm/y)					V_Z (mm/y)				
		97-03	97-05	03-05	Nuvel	EPN	97-03	97-05	03-05	Nuvel	EPN	97-03	97-05	03-05	Nuvel	EPN
1	BRSK	-16.8	-17.1	-19.2	-14.6		20.8	18.2	9.1	18.0		9.5	11.4	16.2	9.1	
2	CSAR	-17.1	-16.8	-15.7	-15.3		18.5	18.5	18.6	17.8		10.2	9.8	8.7	8.7	
3	HVAR	-18.8	-18.9	-19.2	-14.5		21.1	20.2	17.4	18.3		12.9	13.2	14.3	9.4	
4	PENC11206M006	-16.6	-16.6	-16.6	-15.7		18.0	18.0	18.1	17.4		8.2	8.3	8.2	8.3	
5	GRAZ11001M002	-17.5	-17.5	-17.6	-14.8		18.0	18.2	18.2	17.8		8.2	8.1	8.2	8.9	
6	LJUB	-16.2	-16.7	-18.0	-14.4		16.4	17.7	22.0	18.0		11.2	11.3	11.5	9.2	
7	MATE12734M008	-18.8	-18.7	-18.8	-14.3		19.1	19.1	19.1	18.7		13.1	13.0	13.1	9.7	
8	TIS3	-17.1	-16.9	-16.3	-16.3		14.8	16.5	21.4	17.5		10.0	9.1	6.5	8.2	
9	SOFI11101M002	-16.5	-16.6	-16.5	-16.2		18.6	18.7	18.7	17.8		7.4	7.4	7.3	8.5	
10	HARM	-16.3	-16.5	-17.0	-16.7		17.5	20.0	26.8	17.6		7.9	6.8	4.1	8.2	
11	VRN1	-16.0	-17.2	-20.5	-17.2		16.5	17.4	19.4	17.0		6.7	7.3	9.4	7.6	
12	WTZR14201M010	-15.7	-15.7	-15.7	-14.4		17.3	17.2	17.2	17.6		8.7	8.7	8.7	8.8	
13	ZIMM14001M004	-13.8	-13.8	-13.8	-12.9		18.7	18.5	18.4	18.2		10.0	10.0	10.0	9.8	
14	BLGR			-16.1	-15.7				17.3	17.8				9.1	8.6	
15	TIMI			-14.4	-16.0				20.1	17.6				5.9	8.4	
16	BRAI			-15.8	-17.4				21.2	16.9				4.0	7.4	
17	BUCU11401M001			-17.7	-17.0	-17.1			19.2	17.3	18.1			7.6	7.8	8.1
18	KAVA			-16.0	-17.4				20.6	17.2				4.6	7.6	
19	FUN3			-21.1	-16.8				15.9	17.2				12.1	7.8	
20	GABR			-17.7	-16.6				25.1	17.6				5.6	8.2	
21	MALJ			-17.5	-14.2				17.6	18.2				12.6	9.4	
22	SRJV11801S001			-16.8	-15.1	-18.6			19.2	18.1	18.6			10.2	9.0	9.4
23	TUBI20806M001			-17.9	-17.4	-18.8			19.3	17.3	17.4			7.1	7.7	3.9
24	ISTA20807M001			-18.3	-17.3	-17.9			22.3	17.4	20.8			5.9	7.8	6.0
25	ORID15601M001			-15.0	-15.4	-14.8			21.6	18.3	21.0			7.3	9.1	7.9

- **GPS and NUVEL1A-NNR station velocity vectors and their differences are also shown graphically in the figures 5, 6 and 7.**

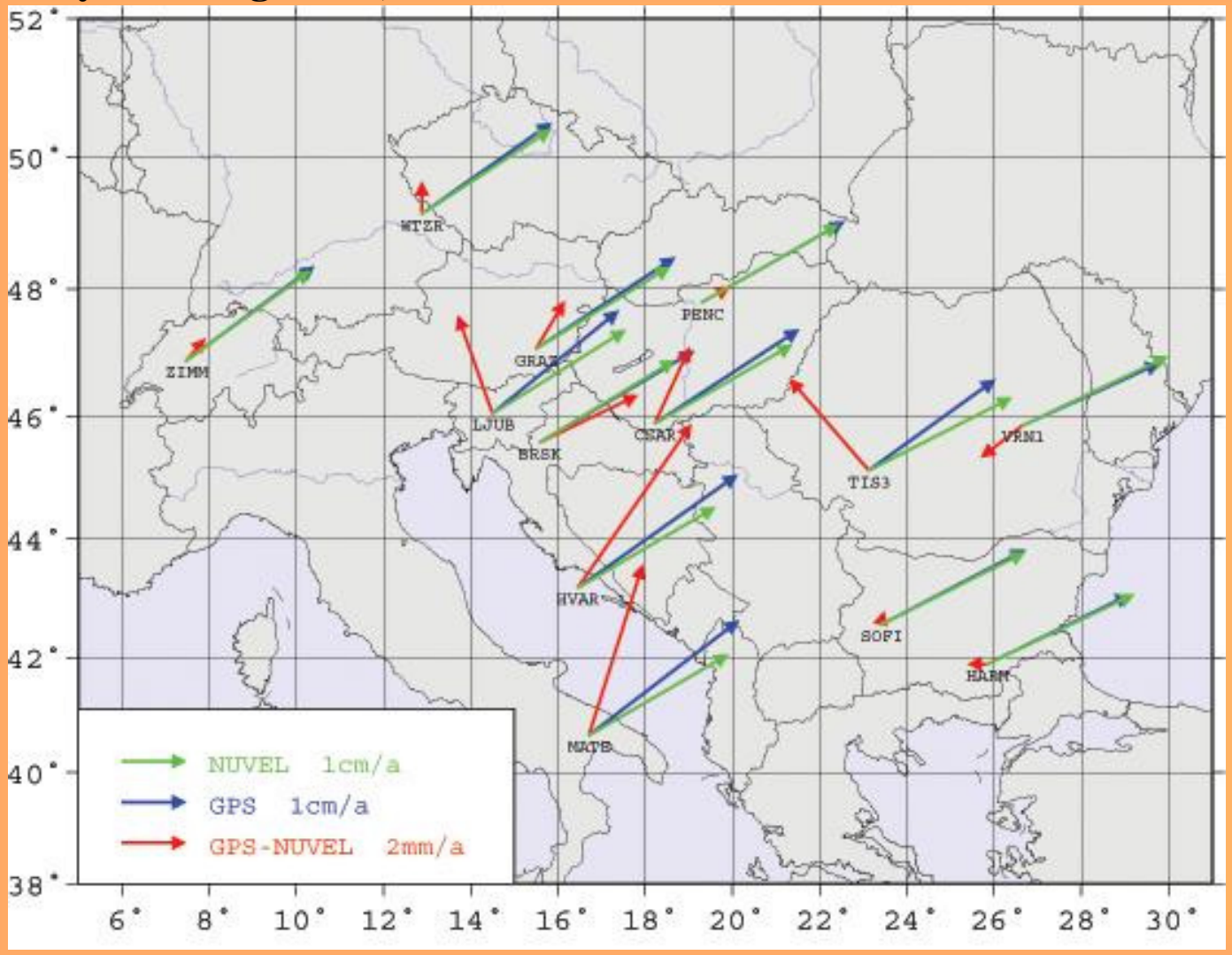

Fig. 5. 97-03'GPS estimated and NUVEL1A-NNR velocity vectors of BP'CEGRN stations and their differences

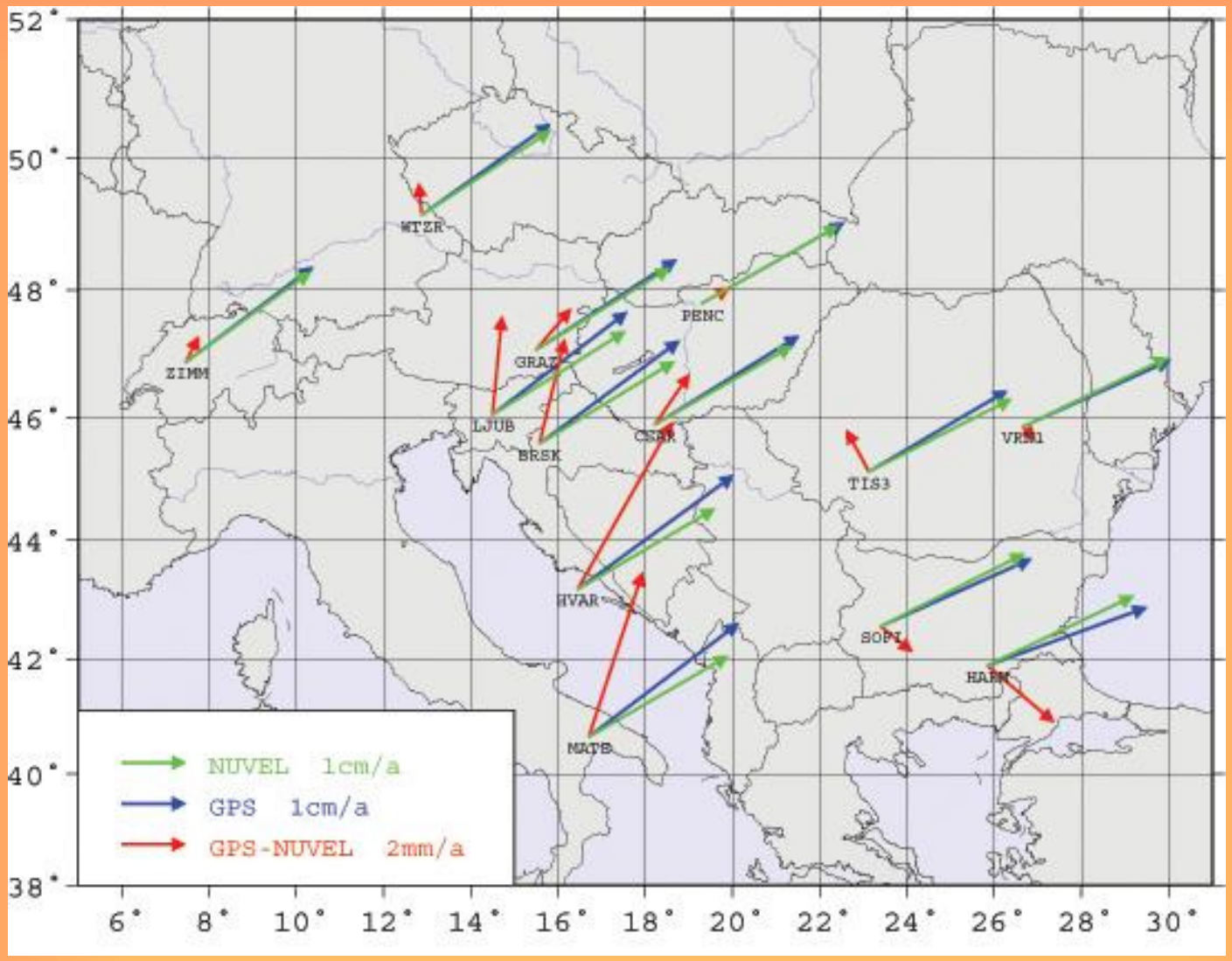

Fig. 6. 97-05'GPS estimated and NUVEL1A-NNR velocity vectors of BP'CEGRN stations and their differences

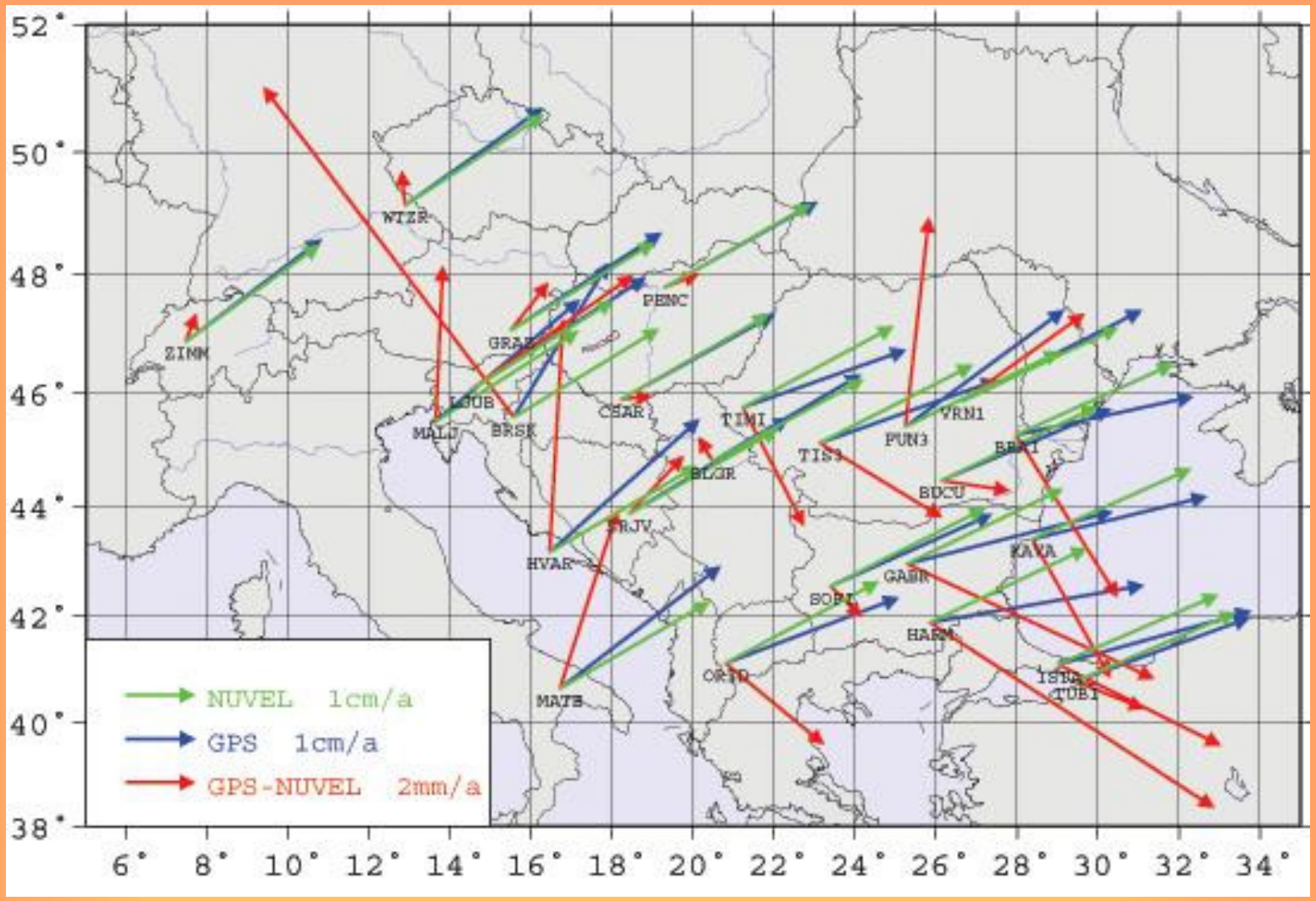

Fig. 7. 03-05'GPS estimated and NUVEL1A-NNR velocity vectors of BP'CEGRN stations and their differences

- **For most of the stations the estimated velocities from all combined solutions agreed very well.**

- **Only estimations in the third combined solution - BP'CEGRN03-BP'CEGRN05 deviate of amount of 1-2.5 mm/y (marked in grey in table 9). These disagreements mainly concern the above established problematic stations.**

- **The agreement with the EPN available estimations (within 0.1-1.9 mm/y) and with the calculated NUVEL–NNR1A velocities are also good with exception for some of the problematic stations.**

- **For some of these stations the problem is probably in 2003 as it is supposed in the analysis above but at present for the most stations it can not be localized the campaign where the problem is without additional information.**

4. Conclusion

- At the first step of this study an attempt to localize the problematic stations and to give some explanation for the problems within the period of three CEGRN campaigns concerning Balkan Peninsula subnetwork is done.

- If the problem occurs only in one campaign participated in the comparison then the error in the suspected stations is related to the measurements in this year and it mainly concerns Up component, i.e. height problem.

- If the problem occurs for the same stations participated in both campaigns then it could be interpreted as an error which is still available in both campaigns or less probably as a movement.

- Estimated station velocities from different combined campaign solutions except the problematic stations agreed very well and they could be used for further investigations and interpretations by other specialists in the earth sciences.