THE USE OF THE GEODETIC METHODS FOR THE EVALUATION OF THE GROUND DISPLACEMENTS

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Abstract

The aim of the paper is to present and analyse the numerical results obtained by the comparison of GPS data and high precision terrestrial measurements performed at four local control networks in Friuli (Italy), Karnten (Austria) and Toscana (Italy) installed in order to detect current crustal deformations.
In the above mentioned networks the distances were measured with Mekometers ME 5000, also geometric and trigonometric levellings were performed. A local 3D free network adjustment was executed for all the classical measurements. The comparison between the adjusted slope distances, ranging from 1 to 13 km, and GPS differences of coordinates was performed. The greater part of the differences between Mekometer and GPS distances is positive, the scale factors are generally of few ppm.

Zusammenfassung

Der Zweck dieses Artikels ist die Vorlegung und Analyse der Ergebnisse, die vom Vergleich zwischen GPS-Messungen und hochpräzisen terrestrischen Messungen stammen, die in vier lokalen Kontrollnetzen in Fnaul (Italien), Karnten (Osterreich) und Toskana (Italien) geführt wurden. Die Netze wurden eingerichtet, um die aktuellen Krustdeformationen zu ermitteln.
In den obengenannten Netzen wurden die Strecken mit Mekometer ME 5000 vermessen, auch geometrische und trigonometrische Nivellierungen wurden geführt. Die terrestrischen Messungen wurden als lokales freies 3D-Netz ausgeglichen. Der Vergleich wurde zwischen den von 1 bis 13 km langen ausgeglichenen schrägen Strecken und den GPS-Koordinatenunterschieden ausgeführt. Die meisten Unterschiede zwischen Mekometer- und GPS-Distanzen sind positiv, die Maastabfaktoren sind normalweise unter wenigen mm/km begrenzt.

1. Introduction

The Dipartimento di Georisorse e Territorio of the Udine University established at different epochs three geodetic networks in Friuli (North-East of Italy) for the detection of ground displacements (fig 1).

Both classic geodetic measurements (distances, horizontal angles, geometric and trigonometric levelling, microgravimetry) and GPS measurements have been performed up to now (Crosilla et al, 1989) with the cooperation of the below listed institutiones:

Osservatorio Geofisico Sperimentale - Trieste

Regione Friuli-Venezia Giulia - Trieste

Faculty of geodesy - University of Ljubljiana

Geodätisches Institut - University of Karlsruhe

Geodätisches Institut - University of Stuttgart

Istituto per lo Studio della Dinamica delle Grandi Masse - Consiglio Nazionale delle Ricerche (CNR) - Venezia (spirit levelling)

Istituto di Geofisica Applicata e Miniere - University of Trieste (microgravimetry).

In order to support and integrate an existing precise levelling control network, in the Travale geothermal area (Tuscany, Italy), the *Istituto Internazionale per le Ricerche Geotermiche of the CNR* of *Pisa* set up a geodetic network in 1980 to monitor the ground displacements occuring as natural neotectonic activity and induced by steam production in the geothermal field.

The most important charachteristic of the four networks are reported in table 1.

Table 1 Geodetic networks. 1 name of the network; 2. number of points, 3 distance measured with the Mekometer ME 5000, 4 year of installation, 5. number of repetitions until 1993, 6 area covered (km x km); 7. mean latitude, 8 mean longitude.

1	2	3	4	5	6	7	8
Caneva	11	28	1985	9	1x2	45°58'	12°27'
Gemona	7	21	1989	3	9x8	46°15'	13°05'
Fella-Gail	10	30	1989	3	17x18	46°33'	13°34'
Travale	7	18	1988	3	8x9	43°11'	11°02'

2. Description of the networks

2.1 Caneva

The Caneva network has small dimensions and is placed north of the town of Caneva in the province of Pordenone close to Veneto. Briefly, the zone is characterized by two different geological units: the northern one is constituted by rigid carbonatic rocks, while the southern one is characterized by plastic terrains composed of psammitic and pelitic units. The contact between the two units takes the form of a disjunctive structure of regional extent (Aviano fault) which runs locally in a South/West - North/East direction.

The network is composed of 11 benchmarks, 6 are located on the carbonatic unit, the remaining 5 on the plastic terrains (fig. 2). The network covers an area between the plain and the mountains, the heights are ranging from 76 m to 170 m and the measured distances from 116 m to 1321 m *(Crosilla, Marchesini, 1989)*.

2.2 Gemona

The Gemona network is located at the epicentral area of the 1976 Friuli earthquake over a great number of thrusts of di-

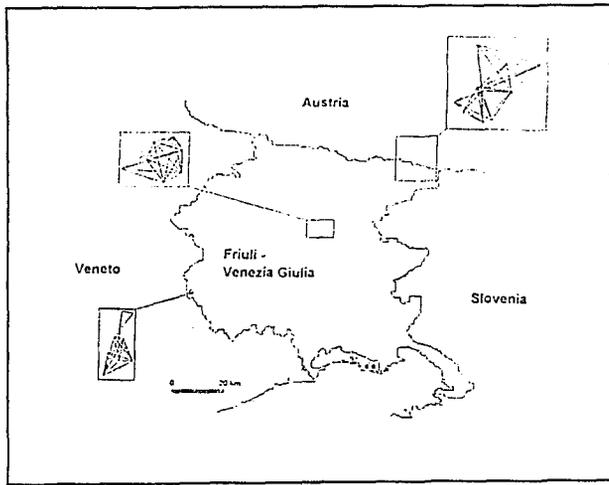Dipartimento di Georisorse e Territorio, Università di Udine
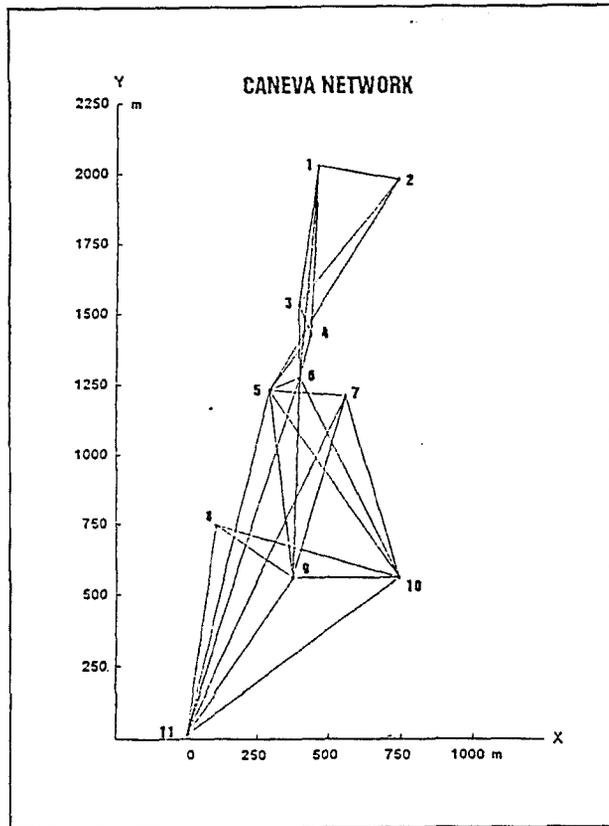
Fig. 1: Geodetic networks in Friuli (Italy).

Fig. 3: The Gemona Network.

Fig. 2: The Caneva Network.

2.3 Fella-Gail

The aim of the Fella-Gail network is to control the actual movements which interest two of the major faults in the Eastern Alps: the Gailtal fault, placed at the east end of the Periadriatic Lineament, and the Fella-Sava fault, that is the middle-eastern part of the Valsugana- Fella-Sava fault-system.

The network, composed of 10 benchmarks, has been installed during spring 1989 across the valley of Fella and Gail. 4 points belong to Italy, 3 to Austria and 4 are situated exactly on the boundary line (fig. 4). The network covers a montaneous area, the benchmarks are mostly on the top of the mountains with heights ranging from 755 m to 2138 m *(Beinat, Marchesini et al, 1991)*.

Fig. 4: The Fella Gail Network.

naric and south alpine direction. The South Alpine system of thrusts is currently more active than the dinaric one, its front is locally represented by the Peri- adriatic thrust which superimpose Mesozoic carbonatic rocks (North) to the Paleogenic Flysch of Friuli.

The network consists of 7 benchmarks (fig. 3) and covers an area between the plain and the mountains, the benchmarks are mostly on hills with heights ranging from 184 m to 709 m and all in sight of each other *(Baldi et al, 1991)*.
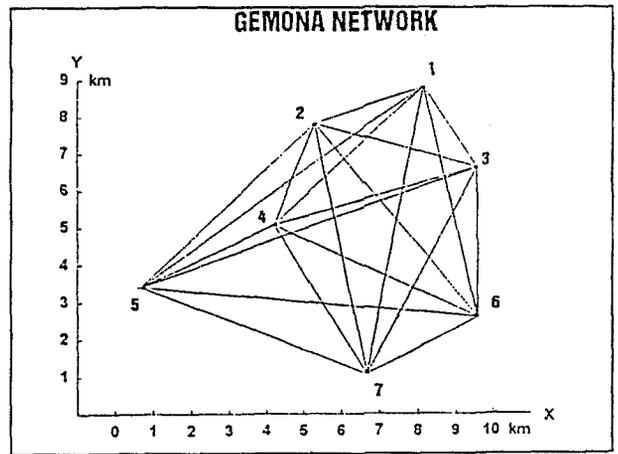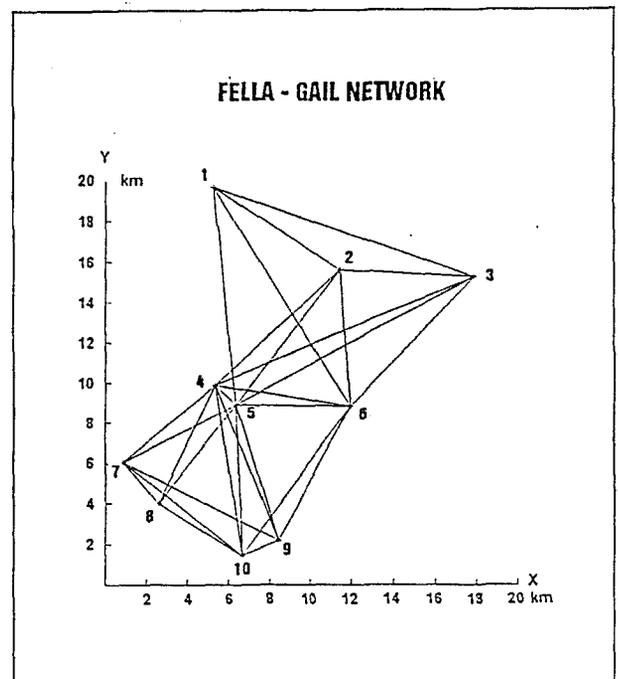
2.4 Travale

The Travale net consists of 7 benchmarks (fig. 5) located across the main distensive fault system at the SW boundary of a regional graben- shaped tectonic feature that trends in Apennine direction. The area is also affected by intensive geothermal exploitation. The network covers a hilly area, the heights of the benchmarks are ranging from 418 m to 854 m *(Beinat, Capra et al, 1991).*
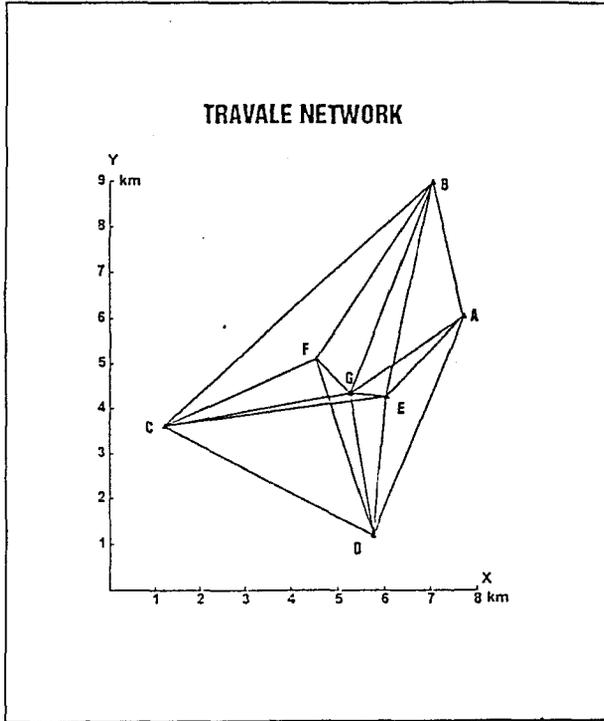

Fig. 5: The Travale Network.

From the point of view of the foundation terrains, A, C and D are buried pillar in soft terrains, E and F are made by bench marks installed on outcropping rocks, G is on a specially costructed monument on the top of a wooded hill made by Gabro rocks, B is on the top of a medieval tower built on cemented conglomerates.

2.5 Monumentation

All the benchmarks of the networks in Friuli consist of a metal rod cemented in the soil to the depth of the bed rock; the reference point is marked on the top of the rod, at the ground level. Three metal pegs, cemented in the soil and with hemispherical heads, are fixed around the rod and surrounded by a manhole cover. On the three pegs a metallic pillar is installed so as to perform distance and angular measurements.

The pillars, specially made for this purpose, are 140 cm high and on the top they have a plate with a forced centering, that can be set exactly vertically to the reference mark on the ground with a special stick equipped with a toric level (fig. 6).

This system makes it possible to obtain a centering precision of a few tenths of millimetres.
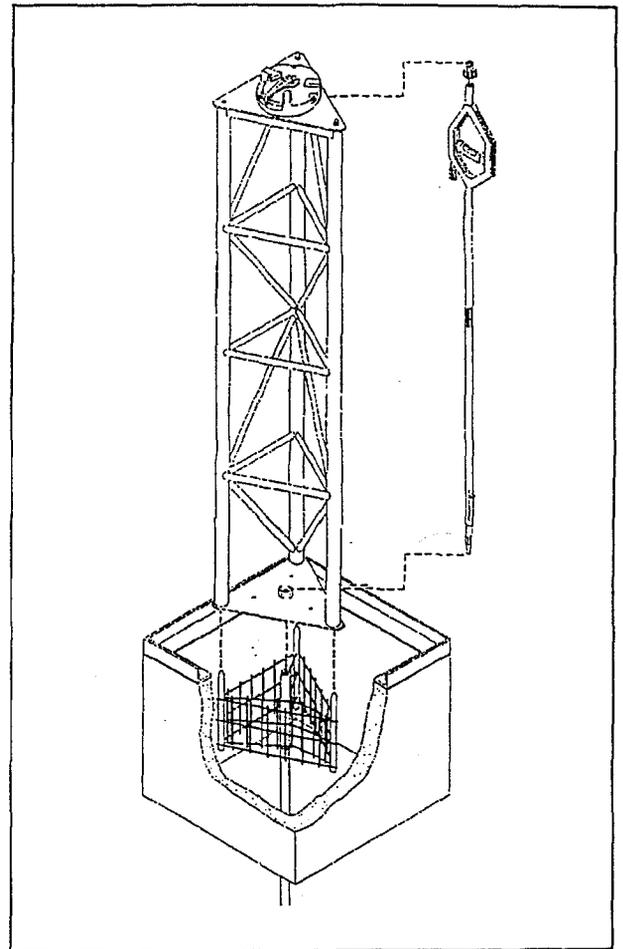

Fig. 6: Monumentation and pillars used.

3. Distance measurements

The distance measurements were performed by the most precise distance meter currently available: the Kern Mekometer ME 5000.

Because of its high intrinsic precision (0.1 mm ± 0.1 mm/km) the fluctuations of the air refraction index along the path of measurement constitute the most important part of the measurement error. For this reason special care was taken with the temperature and pressure detection near both the Mekometer and the prisms.

3.1 Test measurements

The instruments employed in the measurement campaigns were submitted to special tests, performed in a tunnel near Aurisina (Trieste), so as to check the value of the addition constant and the scale factor of a device with respect to the others.

All the possible distance measurements were performed among 4 pillars installed on a straight line along the 500 m long and horizontal tunnel characterized by constant temperature. This fact permits to perform distance measurements without the error due to the variations of the air refraction index. Table 2 summarize the results of one of the above mentioned tests.

Table 2: Test measurements in the Aurisina (Trieste) tunnel.

Point	Adjusted Abscissa		Side	Distance	Residual
	m	mm		m	mm
1	-0.00114 ± 0.04		1 - 2	124.12018	-0.01
2	124.11905 ± 0.03		1 - 3	302.30592	0.03
3	302.30474 ± 0.03		1 - 4	490.22900	0.02
4	490.22784 ± 0.04		2 - 4	366.10879	0.01
			2 - 3	178.18567	-0.02
			3 - 4	187.92309	-0.01

For long distances (up to 9 km) we used special prism holders equipped with 7 prisms, specially made for this purpose; for short distances the holders can support only a 3 prisms set, they are close to each other on a straight line. The distances between the centers of the cube corners are smaller than the Kern ones, so permitting a better reflexion of the laser beam.

By an adjusting screw the prisms were set up in order to have the same optical path of the Kern prisms with respect to the vertical axis. The stability of the temperature and the resolution of 0.01 mm (by means of a laptop computer and the *Promeko* software) permit an accuracy of 0.03 mm.

3.2 Data processing

For each set of data relative to the measurement campaigns that is, distances, horizontal angles (only in the Caneva net) and orthometric height differences, a 3D network adjustment was executed applying the least squares principle and with the further constraint of a minimum norm for the vector of the unknowns. Operating in this way, that is considering a completely free network adjustment, we used the same arbitrary local reference system for all the epochs of measurement.

According to the law of error propagation the m.s.e.'s (σD) a priori used in the adjustment for distance observations were computed with the following formula *(Marchesini, 1990)*.

$$\sigma^2_D = \left[\frac{\delta D}{\delta f} \cdot \sigma_f\right]^2 + \left[\frac{\delta D}{\delta k} \cdot \sigma_k\right]^2 + \left[\frac{\delta D}{\delta t} \cdot \sigma_t\right]^2 + \left[\frac{\delta D}{\delta p} \cdot \sigma_p\right]^2 + \left[\frac{\delta D}{\delta e} \cdot \sigma_e\right]^2$$

The value of the partial derivatives ($\delta D/\delta X$) and of the m.s.e. of the frequency (σ_f), addition constant (σ_k), temperature (σ_t), pressure (σ_p) and humidity (σ_e) are reported in Table 3.

4. Levelling

The benchmarks of the networks of Caneva and Gemona were connected with a high precision spirit levelling measured with high precision level and invar rods. In order to reach 4 points of the Gemona network it was necessary to use the trigonometric levelling for distances ranging from 495 m to 835 m. It was performed with reciprocal measurements of the zenith angles from 2 different points of the geometric levelling net.

In the same manner the heights of 3 points in the Travale and 9 points in the Fella-Gail networks were measured.

Table 3: Computation of the m.s.e. of a distance.

X	$\delta D/\delta X$	σX	
f	$\dfrac{D}{f}$	$1 \cdot 10^{-7} \cdot f$ (f=500 MHz)	f=frequency k=addition constant t=temperature p=pressure e=humidity
k	1	0.2 mm	
t	$D(n_s-1)\dfrac{p \cdot p(g+ah)10^{-6}+a}{q \cdot (1+at)^2}$	$\dfrac{1}{2}\left[2 \cdot \sigma^2_T + \dfrac{D \cdot z^4}{z(1-\Phi_1-\Phi_2)^2}\right]^{\frac{1}{2}}$	q=960,954 g=0,010 h=0,613 a=1/273.15 l=4,04·10⁻⁵
p	$-D(n_s-1)\dfrac{1}{q}\dfrac{1+2p(h-gt)10^{-6}}{1+at}$	0.2 hP	$n_s-1=$ $2.84515 \cdot 10^{-4}$
e	$D \cdot l$	10%	$z^2=0.60°C^2/km$ $\Phi_1=0.36$ $\Phi_2=0.18$ $\sigma_T=2.0°C$

5. GPS Measurements

All points of the networks of Gemona, Fella-Gail and Travale were observed with GPS devices, in particular with Wild in the first net and with Trimble in the last two ones; the small dimensions of the Caneva net suggested to perform GPS measurements only on three points, in two different years *(Schwarz, 1991)*.

All GPS measurement campaigns were performed during 2 or 3 days close the time of the measurement campaigns with the classical instruments.

The data were processed with standard softwares and options: the software package POPS or Trimvec were used, the general solution is a multi-baseline and a multi-session solution. The computation excludes those observations with a minimum elevation less than 15°; the broadcast ephemeris were used. For the tropospheric correction the standard Saastamoinen model was applied, starting from a mean atmospheric model. The ionospheric correction was based on a single-layer model.

6. Comparison between classical and GPS measurements

From the adjusted coordinates calculated with the classical measurements and with the GPS ones we computed the slope adjusted distances and compared the two sets of data. Besides the absolute [MEK-GPS] and relative [(MEK-GPS)/D] differences of the slope distances, the m.s.e. a posteriori (σD) of the distances measured with the Mekometer are also shown (Tab. 4, 5, 6, 7).

The listed global m.s.e. a posteriori ($\sigma \hat{\sigma}$) is coming from the adjustment of the classical measurements.

7. Conclusions

The scale factors (s) between GPS and Mekometer measurements (average of the relative differences) and their error intervals (s ± σ_s) of the networks are represented graphically (Fig. 7) in this way:
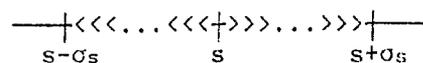
Table 4: Comparison between the slope adjusted distances of the Caneva network

Side	Mekometer δ_D (m)	(mm)	GPS (m)	MEK-GPS (mm)	(MEK-GPS)/D (mm/km)
3 - 10	1039.0307		1039.0232	7.5	7.22
3 - 11	1570.7704		1570.7699	0.6	0.38
10 - 11	917.3799 ± 0.9		917.3978	-17.9	-19.51
3 sides	σo = 1.44		Campaign of 1989, April		
1 - 8	1334.0368		1334.0348	2.0	1.50
1 - 10	1500.6725		1500.6684	1.1	2.73
8 - 10	666.2030 ± 1.0		666.1997	3.3	4.95
3 sides	σo = 2.06		Campaign of 1991, April		
6 sides	1989 + 1991		average m.s.e.	-0.1 ±9.0	-0.46 ±9.65

Table 5: Comparison between the slope adjusted distances of the Gemona network

Side	Mekometer δ_D (m)	(mm)	GPS (m)	MEK-GPS (mm)	(MEK-GPS)/D (mm/km)
4 - 2	2960.4816 ± 1.1		2960.4723	9.3	3.14
4 - 5	3914.3071 ± 1.5		3914.2900	17.1	4.37
4 - 3	5609.0877 ± 2.0		5609.0804	7.3	1.30
4 - 1	5425.4764 ± 1.6		5425.4736	2.8	0.52
4 - 6	5931.5905 ± 2.2		5931.5701	20.4	3.44
4 - 7	4682.5463 ± 1.8		4682.5305	15.8	3.37
7 - 6	3300.5804 ± 1.3		3300.5759	4.5	1.36
7 - 3	6287.5711 ± 2.1		6287.5738	- 2.7	- 0.43
7 - 2	6880.9186 ± 2.1		6880.9001	18.5	2.69
7 - 5	6431.4096 ± 3.0		6431.3813	28.3	4.40
2 - 3	4478.8273 ± 1.7		4478.8207	6.6	1.47
2 - 1	3020.3780 ± 1.1		3020.3779	0.1	0.03
2 - 5	6393.8263 ± 2.3		6393.8051	21.2	3.32
2 - 6	6778.1962 ± 2.2		6778.1766	19.6	2.89
6 - 3	4064.5526 ± 1.5		4064.5551	- 2.5	- 0.62
6 - 1	6392.7882 ± 1.8		6392.7860	2.2	0.34
3 - 1	2625.4687 ± 1.0		2625.4713	- 2.6	- 0.99
1 - 5	9221.7615		9221.7404	21.1	2.29
1 - 7	7871.2013		7871.2003	1.0	0.13
3 - 5	9493.8684		9483.8399	28.5	3.01
5 - 6	8968.4765		8968.4448	31.7	3.53
21 sides	σo = 0.38 1989, April		average m.s.e.	11.82 ±11.18	1.88 ±1.70
4 - 1	5425.4924 ± 2.2		5425.4756	16.8	3.10
1 - 7	7871.2265		7871.1995	27.0	3.43
4 - 7	4682.5478 ± 2.5		4682.5414	6.4	1.37
3 sides	σo = 0.52		Campaign of 1991, April		
24 sides	1989 + 1991		average m.s.e.	12.43 ±10.99	2.00 ± 1.67

Table 6: Comparison between the slope adjusted distances of the Fella-Gail network

Side	Mekometer δ_D (m)	(mm)	GPS (m)	MEK-GPS (mm)	(MEK-GPS)/D (mm/km)
1 - 2	7435.9604 ± 7.3		7435.933	27	3.63
1 - 3	13376.5920 ± 11.3		13376.458	134	10.02
1 - 5	10811.0570 ± 12.1		10811.099	-42	-3.88
1 - 6	12735.8925 ± 9.4		12735.882	11	0.86
2 - 3	6573.1737 ± 5.8		6573.104	70	10.65
2 - 4	8425.8764 ± 6.8		8425.839	37	4.39
2 - 5	8487.0217 ± 6.1		8486.977	45	5.30
2 - 6	6862.8673 ± 6.4		6862.826	41	5.97
3 - 4	13635.6571 ± 7.8		13635.570	87	6.38
3 - 5	13157.5088 ± 7.4		13157.423	86	6.54
3 - 6	8753.1838 ± 2.9		8753.130	54	6.17
4 - 5	1429.3144 ± 0.9		1429.306	8	5.60
4 - 6	6708.1586 ± 4.3		6708.130	29	4.32
5 - 6	5602.1572 ± 3.9		5602.132	25	4.46
7 - 8	2656.4953 ± 1.8		2656.478	17	6.40
7 - 5	6194.4966 ± 4.4		6194.452	45	7.26
8 - 5	6219.3203 ± 4.6		6219.264	56	9.00
8 - 4	6545.0236 ± 4.6		6544.965	59	9.01
7 - 4	5918.6079 ± 5.4		5918.563	45	7.60
7 - 9	8461.8361 ± 4.5		8461.766	70	8.27
9 - 4	8319.6692 ± 4.9		8319.629	40	4.81
9 - 5	7035.2687 ± 4.8		7035.239	30	4.26
9 - 6	7520.4013 ± 6.1		7520.367	34	4.52
23 sides	σo = 0.85 1989, August		average m.s.e.	43.8 ±33.9	5.72 ±3.08

Table 7: Comparison between the slope adjusted distances of the Travale network

Side	Mekometer δ_D (m)	(mm)	GPS (m)	MEK-GPS (mm)	(MEK-GPS)/D (mm/km)
A - B	3016.3430 ± 2.3		3016.3183	+24.7	+ 8.19
A - C	6954.1180		6954.1165	+ 1.5	+ 0.22
A - D	5251.1549 ± 3.3		5251.1333	+21.6	+ 4.11
A - E	2455.0139 ± 1.5		2455.0033	+10.6	+ 4.32
A - F	3308.6535		3308.6444	+ 9.1	+ 2.75
A - G	2991.5356 ± 1.9		2991.5267	+ 8.9	+ 2.98
B - C	7918.6412 ± 5.2		7918.6256	+15.6	+ 1.97
B - D	7902.3773 ± 3.0		7902.3414	+35.9	+ 4.54
B - E	4820.8681 ± 2.8		4820.8654	+ 2.7	+ 0.56
B - F	4601.8092 ± 3.2		4601.7839	+25.3	+ 5.50
B - G	4963.2491 ± 2.9		4963.2513	- 2.2	- 0.44
C - D	5146.3020 ± 4.2		5146.3096	- 7.6	- 1.48
C - E	4869.2946 ± 2.3		4869.2908	+ 3.8	+ 0.78
C - F	3668.5398 ± 2.6		3668.5527	-12.9	- 3.52
C - G	4120.3023 ± 2.4		4120.3048	- 2.5	- 1.61
D - E	3099.9613 ± 1.9		3099.9519	+ 9.4	+ 3.03
D - F	4111.3884 ± 2.2		4111.3754	+13.0	+ 3.16
D - G	3198.7666 ± 1.9		3198.7461	+20.5	+ 6.41
E - F	1706.9470		1706.9343	+12.7	+ 7.44
E - G	774.6535 ± 0.5		774.6381	+15.4	+19.88
F - G	1054.0926 ± 0.7		1054.1013	- 8.7	- 8.25
23 sides	σo = 0.75 1990, June		average m.s.e.	+ 9.4 ±12.4	+ 2.93 ± 5.42

The four computed scale factors are lower or a little over their m.s.e. value. In 83% of cases the Mekometer distances are greather than the GPS ones.

We can note that the intersection of all 68%-probability sets of the scale factors (dotted area) is small but not zero. Despite the diversity of the networks and of the used GPS receivers, a substantial homogeneity of the scale factors is recognizable. The scale factor computed with all the data together (2.85 mm/km) is lower than its m.s.e. (4.65 mm/km), so the question if there exists a significant scale factor between GPS and Mekometer, is yet open.

6. References

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Figure 7: Comparison between scale factors (s) in mm/km
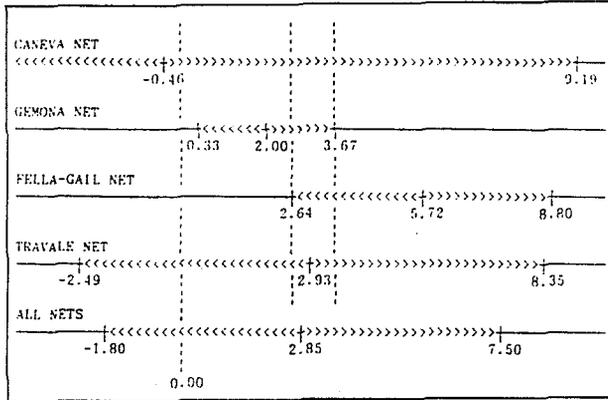
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