Displacement Field Estimation from GPS Measurements in the Volvi Area

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Key words: GPS, Volvi area, Land displacements, Field velocity.

SUMMARY

A deformation study of the earth's crust in the seismic zone of Volvi in Northern Greece is presented. Five GPS campaigns from 1994 to 2003 were carried out for the estimation of ground displacements and velocities. Emphasis is given on the multi-epoch analysis and the problem of the reference frame definition. Furthermore an attempt is made for the interpretation and evaluation of the computed displacements.

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1. INTRODUCTION

The estimation of displacements and deformation parameters of the land is very important in Greece due to its great seismic activity. In May and June of 1978 in the Volvi area a sequence of earthquakes with largest magnitude of Ms=6.5 has occurred. A series of aftershocks with magnitudes up to Ms=5 were followed, seriously affecting the city of Thessaloniki. As a result 45 people were killed and 220 were injured. A total of 9480 buildings were severely damaged and approximately 91000 buildings suffered moderate to minor damage. The area of Volvi is located in the northern part of Greece, about 40 Km NE from the city of Thessaloniki (Mygdonian graben). Its seismic activity is evidenced by several destructive earthquakes that occurred in historical time (Papazachos and Papazachou, 1989).

In 1979, one year after the last strong earthquakes a geodetic network consisting of sixteen pillars (see Figure 1, showing the complete network) was established in the area (Vlachos, 1980). Since then, the network has been re-measured several times, using classical geodetic techniques. In November 1994 a new survey of the volvi network was carried out using solely GPS techniques for the first time (Savvaidis et. al., 1997). The GPS surveys were repeated in 1995-1996 (Fotiou et. al., 2003), 1997 (Savvaidis and Ifadis, 2000) and more recently 2003. Various analysis techniques for plane crustal deformations concerning the Volvi area have been discussed in (Dermanis et.al., 1981). In the present study, all five GPS campaigns are being analyzing for the detection of possible spatial displacements and for the estimation of the corresponding velocity field.

1. GPS CAMPAIGNS AND DATA PROCESSING

The GPS data were collected during five independent campaigns conducted between 1994 and 2003. Each campaign lasted from five to nine consecutive days and from two to three sessions within a day. For the 1994-1997 and 2003 campaigns, dual frequency GPS receivers from Ashtech and Leica were used, while for the 1995 and 1996 campaigns only Leica dual frequency receivers were used because less number of pillars was occupied. At least two points were kept common in any successive pair of sessions. Recording time varies from two until ten hours of continuous data with 30-sec. observation rate and 15° cut-off angle. The scope of these points is to link sites (from different sessions) which were not measured simultaneously.

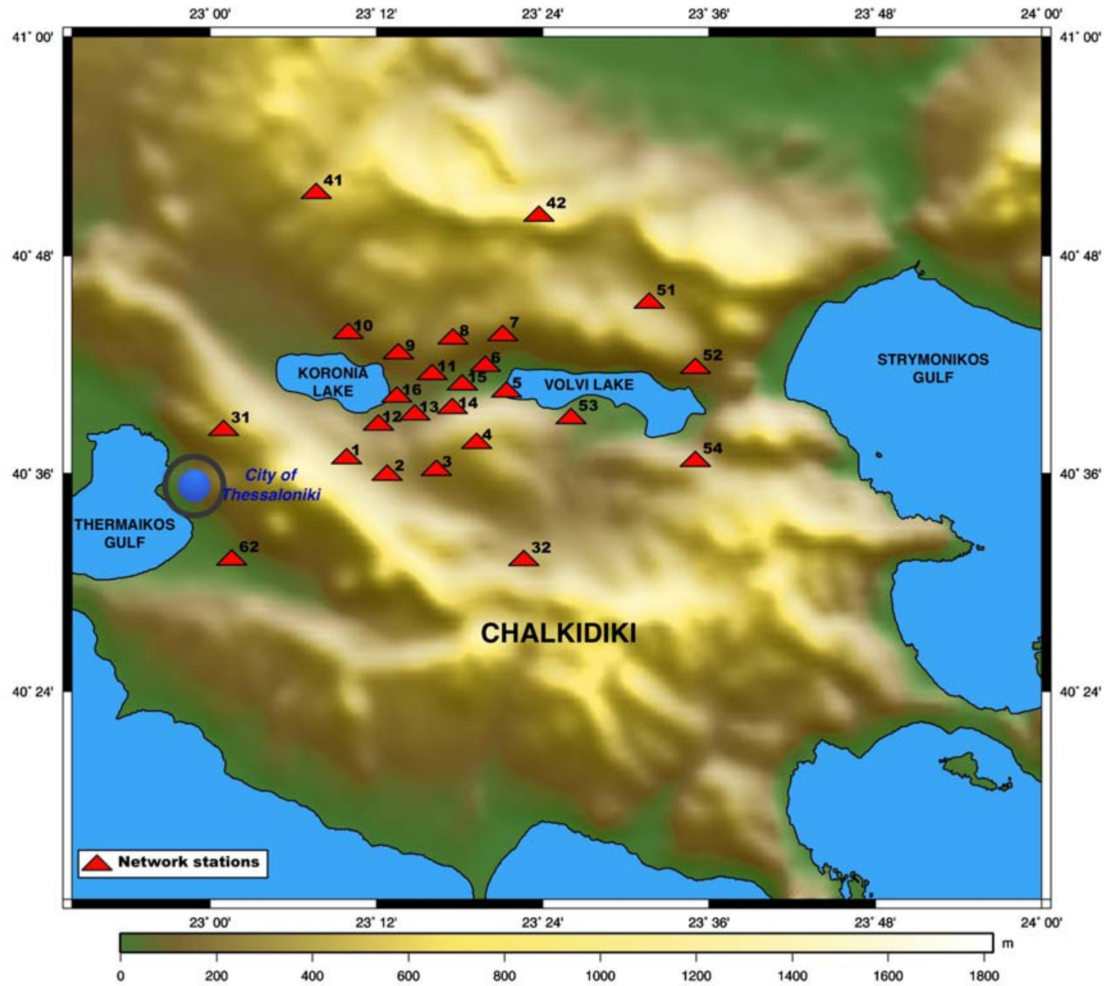

Fig 1: The GPS Stations of Volvi Network (Northern Greece)

This is the classic scheme, when there are more sites to measure than receivers available.
Data were processed on a daily session basis, using precise ephemerides and Hopfield's model to account for the tropospheric refraction. In order to avoid the effect of mixing different antennas, all the phase offsets and variations were properly imported in the processing software. The final solution was derived for the small baselines (<5Km) directly from L1 and L2 ambiguity resolution (introducing local ionospheric models) in order to avoid the noise amplification using the L3 linear combination. For all the others the ionospheric-free fixed solution was used. All the unknown ambiguities numbers are fixed correctly to their integer values using the FARA strategy. These solutions (for each session) enable us to 'clean' the data. i.e. to isolate bad observing windows contaminated with heavy multipath. Each of these solutions provides a first impression about the internal accuracy of the measured baselines. Plotting the computed RMS versus baseline length for the 2003 campaign we detect values between 0.03 mm to 0.5 mm as shown in figure 2. Same values were also extracted for the rest of the campaigns.

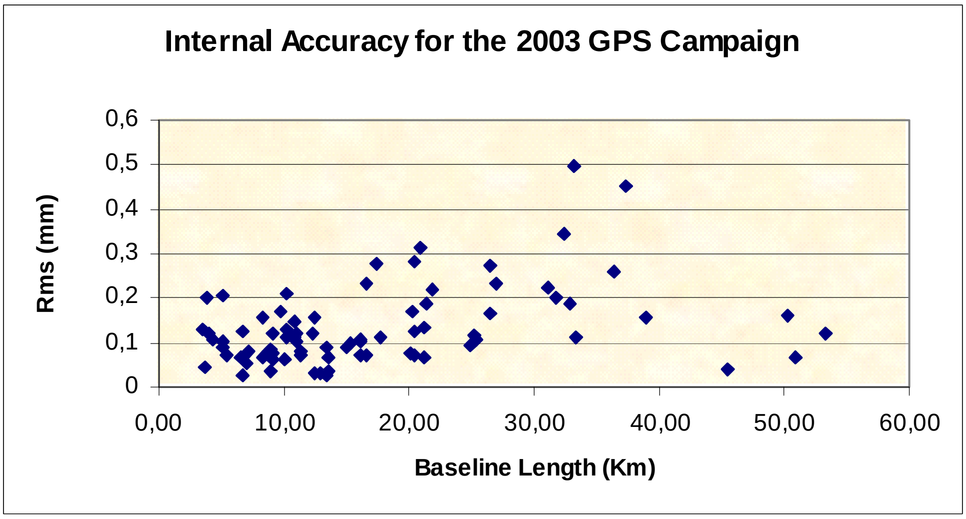

Fig. 2: Baselines Internal Accuracies for the 2003 GPS Campaign Solution

2. THE NETWORK ADJUSTMENT FOR EACH EPOCH

Our analysis is based upon a specially developed algorithm. From the baseline solution of each day separately we obtain the estimation of point coordinates (x, y, z) and their full covariance matrices. The 3-D network adjustment of each campaign follows using as observations the results of the previous adjustments and considering the corresponding days as belonging to the same epoch (year). This is usually valid since the time span for each campaign limited to a few consecutive days.

In order to eliminate the differences between the coordinates of the various campaigns due to their different datums definition in each epoch network adjustment, we have used the same approximate coordinate values and we have applied partial inner constrains on the common points which exists in all five GPS campaigns. In addition, proper statistical tests were applied in order to detect possible systematic errors and outliers for each epoch. In table 1 the coordinates displacements with their error ellipses for the common points between consecutive campaigns are presented. The comparison between the surveys of 1979 and 1994 has given evidence of active extension in the N-S direction, at a rate of roughly 8 cm in 15 years (approximately 5-6 mm/year). These results from geodetic data, are consistent with the direction of extension deduced from the analysis of focal mechanisms of the 1978 earthquake, from microearthquake data, as well as from the observation of the 1978 surface faults (Martinod et al., 1997).

Table 1. Horizontal Displacements Between Successive Epochs

id	Displacements			Error Ellipses			Years
	dx (cm)	dy (cm)	Ds (cm)	a (cm)	B (cm)	ϑ (grad)	
7	0.09	-0.50	0.50	0.3	0.2	182.90	1994-1995
	0.48	0.41	0.63	0.4	0.3	177.70	1995-1996
	-0.72	-0.05	0.72	0.3	0.2	176.41	1996-1997
	1.08	-0.14	1.09	0.5	0.3	180.21	1997-2003
33	0.52	-0.92	1.05	0.3	0.3	182.13	1994-1995
	0.05	-0.77	0.77	0.4	0.3	174.73	1995-1996
	-0.26	1.20	1.23	0.3	0.2	170.54	1996-1997
	0.00	-0.59	0.59	0.3	0.2	180.02	1997-2003
5	0.16	-0.07	0.18	0.5	0.3	181.73	1994-1995
	0.42	0.28	0.50	0.5	0.3	179.98	1995-1996
	-0.67	0.166	0.70	0.2	0.2	174.53	1996-1997
16	0.22	0.98	0.24	0.4	0.3	181.95	1994-1995
	-0.16	-0.32	0.36	0.4	0.3	179.13	1995-1996
	-0.46	0.29	0.54	0.3	0.2	179.64	1996-1997
	0.23	-0.21	0.32	0.3	0.2	177.55	1997-2003
10	0.56	-0.25	0.56	0.8	0.4	189.32	1994-1995
	-0.64	0.55	0.85	0.9	0.4	188.44	1995-1996
9	0.96	0.70	1.19	0.5	0.3	185.96	1994-1995
	-0.61	-0.07	0.61	0.4	0.3	184.60	1995-1996
	-0.32	-0.15	0.36	0.3	0.2	183.33	1996-1997
	0.40	-0.12	0.43	0.5	0.2	173.98	1997-2003
15	0.53	-0.09	0.53	0.3	0.2	183.76	1995-1996
	-0.99	0.11	1.00	0.2	0.2	175.36	1996-1997
	0.83	-0.14	0.85	0.4	0.2	180.36	1997-2003
17	1.00	0.25	1.03	0.3	0.2	172.97	1995-1996
13	-0.03	0.24	0.24	0.3	0.3	168.64	1995-1996
11	0.62	0.01	0.63	0.4	0.3	174.48	1995-1996
4	-1.82	-0.11	1.82	1.1	0.4	179.22	1996-1997
	0.67	0.17	0.70	0.3	0.2	178.94	1997-2003
1	-0.04	-0.21	0.32	0.3	0.2	180.79	1997-2003
32	0.47	-2.34	2.40	0.3	0.2	180.44	1997-2003
31	-1.06	-0.36	1.12	0.6	0.3	183.96	1997-2003
42	1.18	1.09	1.61	0.9	0.5	178.30	1997-2003
52	2.11	-0.11	2.12	0.6	0.4	183.57	1997-2003
53	1.12	-1.06	1.55	0.5	0.3	181.57	1997-2003
54	1.34	1.53	2.04	0.5	0.3	183.29	1997-2003

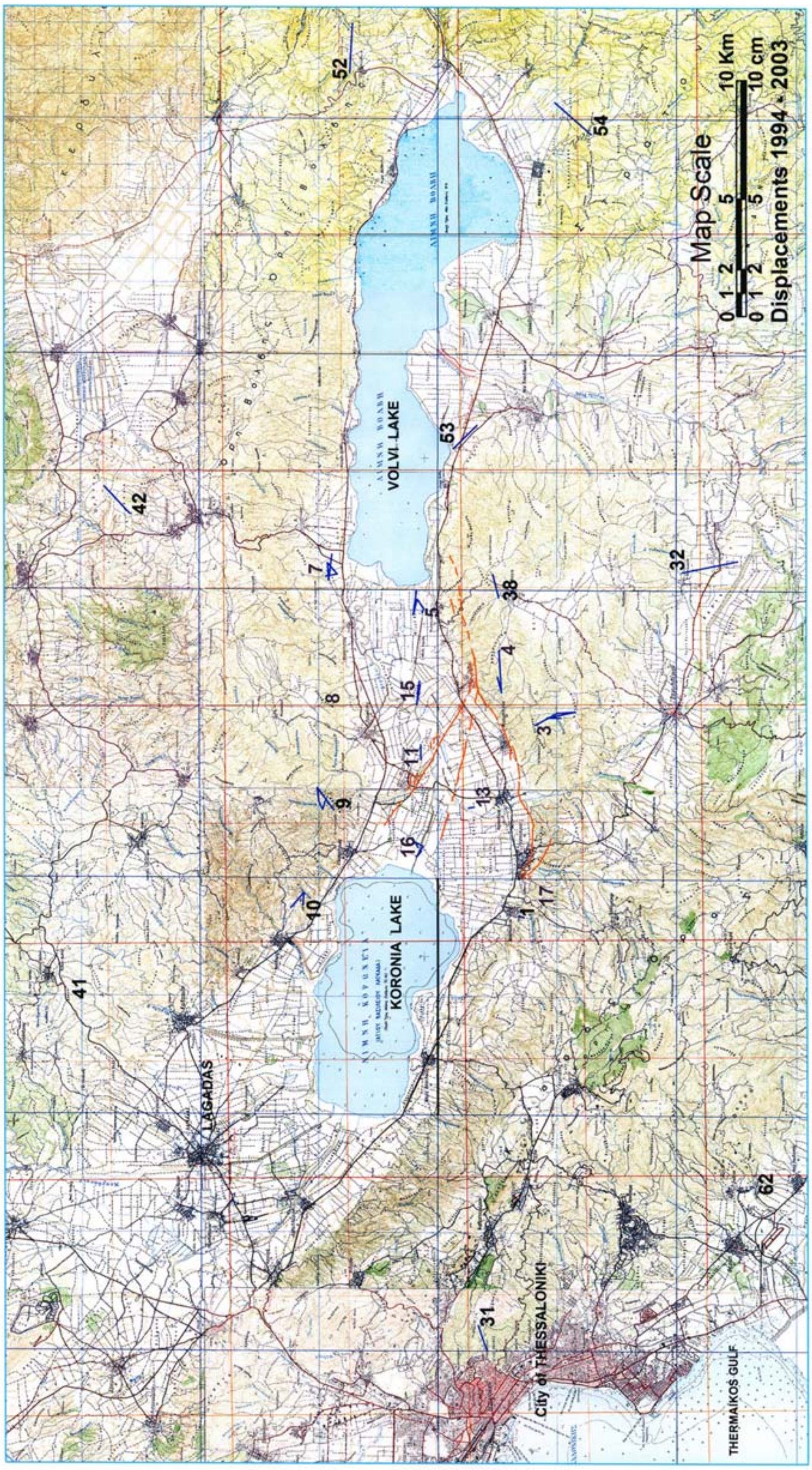

Fig.3. Point displacements between epochs from 1994 to 2003 according to Table 1

In addition, a combination of seismological, neotectonic and gravimetric data indicates that a significant decrease of active deformation and the related seismicity has occurred since 1991-

1992 in the area (Papazachos et. al., 2003). This result is in good agreement with the displacement data of the control network stations, as obtained by the GPS campaigns from 1994 to 2003 and described in this paper.

3. SIMULTANEOUS ADJUSTMENT OF ALL EPOCHS AND VELOCITY FIELD ESTIMATION

The adjusted coordinates of each network campaign are re-adjusted taking into account a deformation model. Under the hypothesis of a smooth motion in the deformation area the vector of the displacements is a function of the velocity displacement and the acceleration according to the model:

$\mathbf{x}_\alpha = \mathbf{x}_o + \delta t_\alpha \dot{\mathbf{x}}$ + **Error!** $\delta t_\alpha^2 \ddot{\mathbf{x}}$. ... where $\delta t_\alpha = t_\alpha - t_o$.

Considering a homogeneous displacement field in time only the linear part of the above equation is used. Therefore the system of observation equations for the m epochs is formulated by:

$$\mathbf{x}_1^b = \mathbf{x}_o + \delta t_1 \dot{\mathbf{x}} + \mathbf{v}_1$$
$$\vdots$$
$$\mathbf{x}_\alpha^b = \mathbf{x}_o + \delta t_\alpha \dot{\mathbf{x}} + \mathbf{v}_\alpha$$
$$\vdots$$
$$\mathbf{x}_m^b = \mathbf{x}_o + \delta t_m \dot{\mathbf{x}} + \mathbf{v}_m \,, \quad \sum_{\alpha=1}^{m} \mathbf{v}_\alpha^T \mathbf{W}_\alpha \mathbf{v}_\alpha = \min.$$

where $\mathbf{x}_o$ is the vector of coordinate corrections for the reference epoch. $\mathbf{x}_1^b \ldots \mathbf{x}_m^b$ are the vectors of each network adjusted coordinates (introducing partial inner constrains) of the epochs t_1. … t_m and $\mathbf{W}_\alpha = \mathbf{C}_a^-$ or $\mathbf{W}_\alpha = (\mathbf{C}_o + \tilde{\mathbf{C}}_\alpha)$ in case the reference epoch t_o is also an epoch of observations.

In the present study the velocity vectors with their associated confidence ellipses were computed for the five GPS campaigns and for the points which participate to at least three epochs, in order to get an impression of using all the GPS data. The corresponding results are presented in Table 2.

Table 2. Velocities of the Coordinates and Confidence Error Ellipses (1-α = 0.95) for the Volvi Network in Epochs 1994,1995,1996,1997 and 2003 (GPS Network).

Id	Velocities (cm/year)			Confidence Error Ellipses								
				(x, y) plane			(x, z) plane			(y, z) plane		
	u;˙;^	v;˙;^	w;˙;^	a (cm)	b (cm)	ϑ (grad)	a (cm)	b (cm)	ϑ (grad)	a (cm)	B (cm)	ϑ (grad)
7	0.15	0.18	0.11	0.872	0.423	69.67	0.921	0.498	58.10	0.747	0.473	33.39
3	0.08	0.04	0.04	0.623	0.324	71.60	0.697	0.374	57.22	0.548	0.349	30.40
5	-0.71	-0.17	-0.60	0.598	0.324	70.56	0.647	0.349	57.99	0.523	0.324	32.74

Id	Velocities (cm/year)			Confidence Error Ellipses (x, y) plane			(x, z) plane			(y, z) plane		
16	-0.71	-0.32	-0.70	0.672	0.349	74.11	0.722	0.398	60.11	0.573	0.349	32.55
10	0.13	0.02	0.16	0.573	0.324	69.80	0.623	0.349	55.76	0.523	0.324	31.87
9	0.22	0.10	0.25	0.946	0.498	76.32	1.046	0.548	59.81	0.822	0.498	31.41
1	0.47	0.07	0.11	1.245	0.697	71.85	1.370	0.772	56.06	1.170	0.647	34.46
4	0.70	0.32	0.48	1.021	0.498	68.40	1.121	0.573	54.78	0.921	0.573	31.04
32	0.68	0.37	0.14	1.245	0.573	69.58	1.394	0.672	54.41	1.121	0.647	29.64
42	-0.15	0.14	0.13	0.822	0.448	69.45	0.896	0.473	55.98	0.747	0.473	32.92
15	0.21	0.15	0.12	0.722	0.374	70.68	0.772	0.448	58.91	0.623	0.423	31.30

4. CONCLUDING SUMMARY

The geodetic network in the area of Volvi Lake was established and measured by classical techniques in 1979, one year after the big Thessaloniki earthquake. Since then it was repeatedly observed by classical triangulation and trilateration methods until 1994. The analysis of the geodetic data until the 1992 epoch, showed significant displacements. This conclusion is consistent with other investigations based on seismological, neotectonic and gravimetric analyses.

Starting 1994, the extended Volvi network was measured by GPS in five epochs (1994, 1995, 1996, 1997, and 2003). The analysis of the GPS data shows that there is a slight relaxation of the deforming body in general, with the exception of a few points. Using in the observation adjustment a linear model for the velocity field, the estimation of the corresponding velocity vectors are within their confidence error ellipses ($1-\alpha = 0.95$). This result enforces the conclusion that currently (over the past seven years) the area is geotectonically non active.

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