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GEODETICALLY DERIVED DISPLACEMENTS AND CRUSTAL DEFORMATION ANALYSIS: APPLICATION IN THE VOLVI AREA

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Abstract

In order to extract displacements and crustal deformation parameters various geodetic methods and algorithmic techniques are presented and rigorously applied. Geodetic measurements carried out from 1979 until 2003 at the network of Volvi area in northern Greece are systematically analyzed. The corresponding analysis and computational process can be described by a combination of the following three steps :

a. Comparison of the results as obtained by independent net adjustments between any two epochs of observations. Therefore the connection of the time spanned network configurations is achieved.

b. Application of prediction techniques on the former results, such as least square collocation, and estimation of deformation parameters for the network area.

c. Simultaneous adjustment of all epochs, including extended adjustment models, e.g. the velocity model.

In each step a statistical assessment must be performed in order to test the significance of the estimated displacements. Finally, the interpretation of the results at the interesting area of the Volvi Lake is attempted.

1. Introduction

The estimation of displacements and deformation parameters of the land is very important in Greece due to its great seismic activity. The Volvi area is located at the northern part of Greece (Central Macedonia) and about 40 km from the city of Thessaloniki. The wide area 40 km × 25 km which includes two lakes (Lagada and Volvi) is one of the geodynamically interesting areas (Papazachos et al., 1979). The largest shocks occurred on May 23, 1978 (Ms=5.8), June 19, 1978 (Ms=5.2) and June 20, 1978 (Ms= 6.5) followed by a series of aftershocks with magnitudes up to 5.0 affecting seriously the city of Thessaloniki.

In order to contribute to the respective geodynamical studies and investigations a monitoring geodetic network with sixteen pillars was established soon after the great shocks and measured since then eventually. Classical measurements of angles and distances are available for the epochs 1979, 1981, 1982, 1983, 1989 and 1990 while GPS measurements performed in 1995, 1997 and 2003. This data was analyzed and used in the present study.

For the determination of displacements and deformation parameters in time and space various geodetic methods have been proposed and recognized as useful techniques in many geophysical studies (Chrzanowski, et al. 1983, Papo and Perelmuter 1983, Rossikopoulos 2001, Rossikopoulos and Fotiou 2001). In the present work some methods and algorithmic techniques are rigorously applied. The analysis includes three main steps followed by proper statistical evaluation.

2. Comparison between two epochs

It is well known that the elimination of the difference between coordinates in two distinct epochs t_a and t_b, due to their different datum definition, is obtained by the optimal fitting of t_b to the t_a coordinates of the reference epoch, applying the similarity transformation. In our case an equivalent technique was applied using the same approximate coordinates for each separate epoch adjustment and introducing partial inner constrains for the common points in all observing epochs (from 1979 to 1997). A future goal is to combine the latest GPS data (2003) with the previous classic observations.

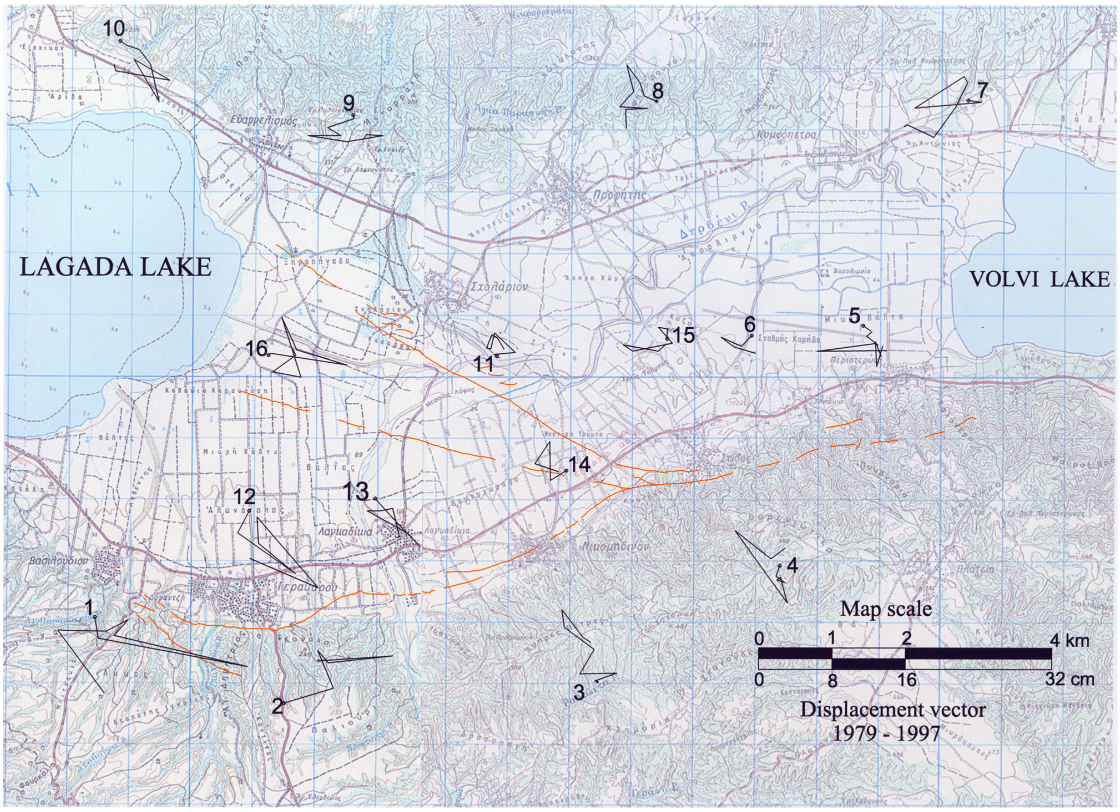

Fig. 1 The vectors of coordinate differences from 1979 until 1997 in the Volvi network

In Fig. 1 the vectors of coordinate differences are mapped from epoch to epoch for all points of Volvi network where the three main fault lines are also shown. It is obvious that almost all points tend to follow a random circular motion. In order to test the significance of the coordinate differences, i.e. to detect possible displacements, hypothesis testing has been applied for all pairs of consecutive epochs by means of the corresponding confidence ellipses.

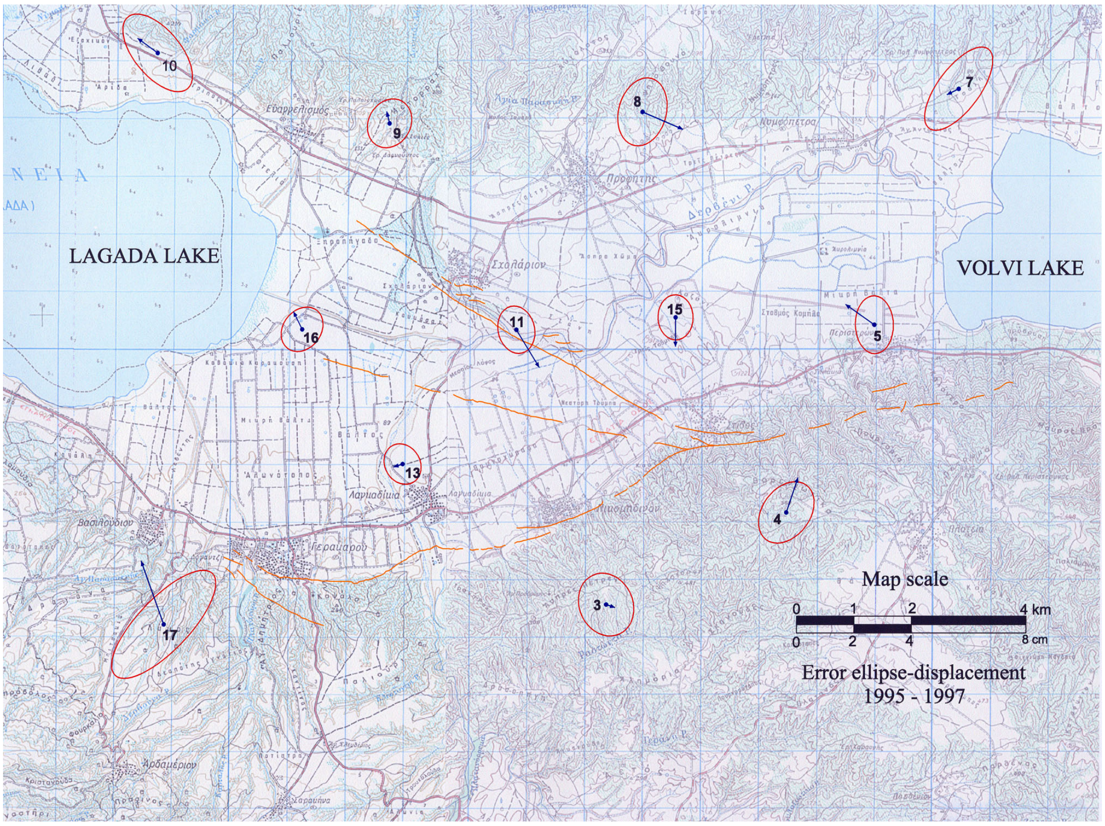

Fig. 2 The vector of coordinate differences and their confidence error ellipses (1− a = 0.95) between 1995 and 1997.

Fig. 2, is a representative one between the epochs 1995 and 1997, where in some points the existence of possible displacements is obvious. Possible displacements are evident in almost all pairs of epochs but in different points and directions of the Volvi network complicating the interpretation of the results.

3. Exact collocation method for the prediction of crustal deformation parameters

Let **u** and **v** the vectors of coordinate differences in x and y directions between two epochs. The prediction of deformation parameters in any point at the network area may be described as follows:

The process starts with the computation of vectors $\boldsymbol{\xi}$ and $\boldsymbol{\eta}$ by,

$$\boldsymbol{\xi} = \mathbf{K}^{-1}\,\mathbf{u} \;, \qquad \boldsymbol{\eta} = \mathbf{K}^{-1}\,\mathbf{v} \tag{1}$$

where **K** is the covariance matrix of the displacements, with elements $K_{ij} = K(S_{ij})$, usually expressed by the exponential function

$$K(S_{ij}) = k_o^2\, e^{\sigma_o^2 S_{ij}^2} \tag{2}$$

with k_o^2 and σ_o^2 unknown parameters in general. The variance σ_o^2 is determined so that

$$K(R) = k_o^2\, e^{-\sigma_o^2 R^2} = \frac{1}{2} \quad \Rightarrow \quad \sigma_o^2 = \frac{\ln 2}{R^2} \quad \Rightarrow \quad K(S_{ij}) = \frac{k_o^2}{2^{(S/R)^2}} \tag{3}$$

where R a mean distance between points. In the case of exact collocation, as in our case, $k_o = 1$.
In any point P(x, y) the following partial derivatives are computed:

$$\frac{\partial u}{\partial x} = \sum_{i=1}^{N} \frac{\partial K}{\partial x} \xi_i = \sum_{i=1}^{N} \frac{x - x_i}{S_i} \frac{\partial K}{\partial S_i} \xi_i \qquad \frac{\partial u}{\partial y} = \sum_{i=1}^{N} \frac{\partial K}{\partial y} \xi_i = \sum_{i=1}^{N} \frac{y - y_i}{S_i} \frac{\partial K}{\partial S_i} \xi_i$$

$$\frac{\partial v}{\partial x} = \sum_{i=1}^{N} \frac{\partial K}{\partial x} \eta_i = \sum_{i=1}^{N} \frac{x - x_i}{S_i} \frac{\partial K}{\partial S_i} \eta_i \qquad \frac{\partial v}{\partial y} = \sum_{i=1}^{N} \frac{\partial K}{\partial y} \eta_i = \sum_{i=1}^{N} \frac{y - y_i}{S_i} \frac{\partial K}{\partial S_i} \eta_i \qquad (4)$$

where x_i, y_i are the coordinates of the network points. The dilatation T, the maximum shear strain γ and the rotation ω (the deformation parameters) are given by

$$\gamma_1 = \sum_{i=1}^{N} \frac{\partial K}{\partial S_i} \left(\frac{x - x_i}{S_i} \xi_i - \frac{y - y_i}{S_i} \eta_i \right) \qquad \gamma_2 = \sum_{i=1}^{N} \frac{\partial K}{\partial S_i} \left(\frac{y - y_i}{S_i} \xi_i + \frac{x - x_i}{S_i} \eta_i \right)$$

$$\gamma = \sqrt{\gamma_1 + \gamma_2}$$

$$\Delta = \sum_{i=1}^{N} \frac{\partial K}{\partial S_i} \left(\frac{x - x_i}{S_i} \xi_i + \frac{y - y_i}{S_i} \eta_i \right) \qquad \omega = \sum_{i=1}^{N} \frac{\partial K}{\partial S_i} \left(\frac{y - y_i}{S_i} \xi_i - \frac{x - x_i}{S_i} \eta_i \right) \qquad (5)$$

An application of this method is presented more extensively in Dermanis et al. (1981). The above algorithm has been applied in all consecutive pairs of epochs (79–80, 80–81, 81–82, 82–83, 83–89, 89–90, 90–95, 95–97). In all pairs of epochs a similar systematic pattern, as in Fig. 3 for the case of γ – maximum shear strain, exists. The same is true for the case of T – dilatation. This situation enforce the previous conclusion that there are certain systematic displacements in the area.

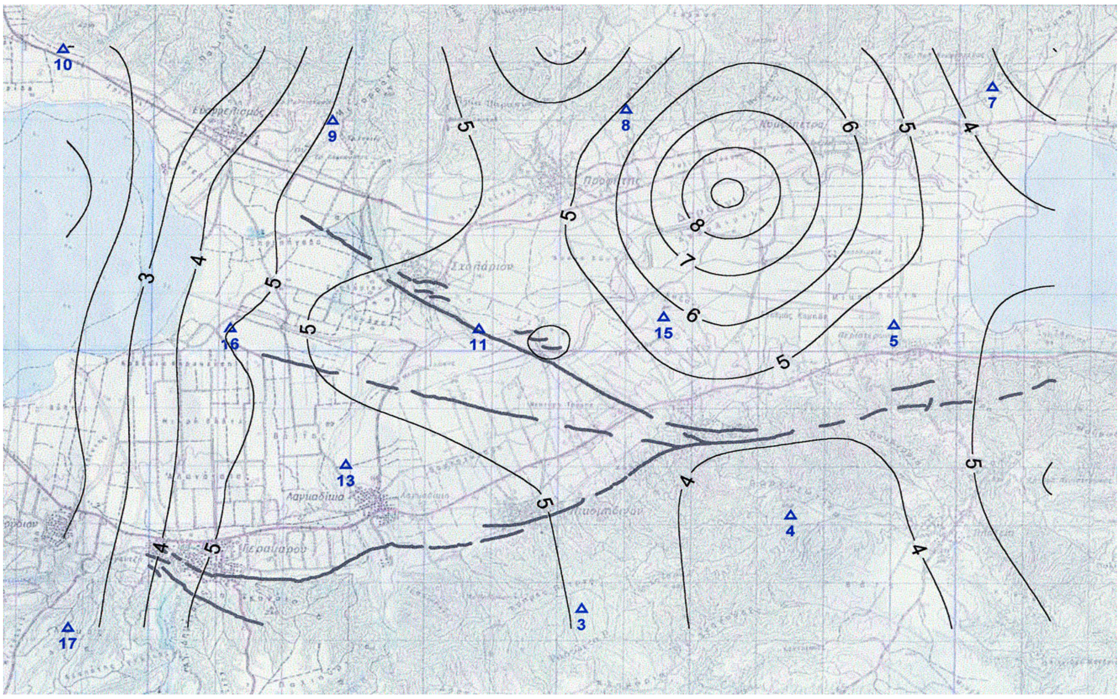

Fig 3. The maximum shear strain γ ($\gamma \times 10^{-6}$) between epochs 1995 –1997 of Volvi network using the collocation method with mean distance R=4 km.

4. Simultaneous adjustment of all epochs and velocity field estimation

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:

$$\mathbf{x}_\alpha = \mathbf{x}_o + \delta t_a \, \dot{x} + \frac{1}{2}\, \delta t_a^2 \, \ddot{x}. \qquad \ldots \qquad \text{where} \qquad \delta t_\alpha = t_\alpha - t_o \; . \tag{6}$$

Applications of this model are given by Papo and Perelmuter (1983) and Rossikopoulos et al. (1998).

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:

$$\begin{aligned} \mathbf{x}_1^b &= \mathbf{x}_o + \delta t_1 \dot{\mathbf{x}} + \mathbf{v}_1 \\ &\vdots \\ \mathbf{x}_\alpha^b &= \mathbf{x}_o + \delta t_a \dot{\mathbf{x}} + \mathbf{v}_\alpha \\ &\vdots \\ \mathbf{x}_m^b &= \mathbf{x}_o + \delta t_m \dot{\mathbf{x}} + \mathbf{v}_m \; , \quad \sum_{\alpha=1}^{m} \mathbf{v}_\alpha^T \mathbf{W}_\alpha \mathbf{v}_\alpha = m \end{aligned} \tag{7}$$

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 the transformed coordinates of the epochs $t_1, \ldots t_m$ and $\mathbf{W}_\alpha = \mathbf{C}^-$ or $\mathbf{W}_\alpha = (\mathbf{C}_o + \mathbf{C}_\alpha)^-$ in case the reference epoch t_o is also an epoch of observations. For the choice of the generalized inverse of the non–positive covariance matrix $\mathbf{C}_\alpha$, see Bjerhammar (1973) or Uotila (1974).

Figure 4 shows the point velocity vectors of Volvi Network as derived from the simultaneous adjustment of epochs 1979, 1981, 1982, 1983, 1989, 1990, 1995 and 1997 with their confidence ellipses. In this figure we notice that the velocities for all points are marginally insignificant.

In the present study the velocity vectors with their associated confidence ellipses were also computed for the three GPS observing epochs (1995, 1997 and 2003) in order to get a first impression using the recently obtained GPS data. The corresponding numerical results are presented in Tables 3 and 4. For these epochs the same conclusion as above can be derived for the velocity vectors.

Table 3. A–posteriori adjustment parameters for 1995, 1997 and 2003 epochs (GPS Network).

	Variance Components			Global
	1995	1997	2003	
Sum of Weighted Squares ($\hat{\varphi}_i$)	0.2482	0.3585	0.0665	0.6732
Degrees of Freedom (f_i)	8.39	11.38	1.64	21
Number of Observations (n_i)	21	21	21	
Variance ($\hat{\sigma}_i^2$)	0.0296	0.0315	0.0405	0.0321
St. Deviation ($\hat{\sigma}_i$)	0.17	0.18	0.20	0.18

Table 4. Velocities of the coordinates and error ellipses for the Volvi network in epochs 1995, 1997 and 2003 (GPS Network).

i	Velocities (cm/year)			Error Ellipses								
				(x, y) plane			(x, z) plane			(y, z) plane		
	$\hat{\dot{u}}$	$\hat{\dot{v}}$	$\hat{\dot{w}}$	a (cm)	b (cm)	ϑ (grad)	a (cm)	b (cm)	ϑ (grad)	a (cm)	b (cm)	ϑ (grad)
7	0.12	0.17	0.22	0.14	0.06	71.16	0.15	0.08	59.30	0.12	0.07	31.26
3	0.03	−0.02	0.00	0.10	0.05	72.96	0.11	0.06	55.96	0.08	0.05	25.88
5	−0.53	−0.12	−0.43	0.10	0.05	71.11	0.11	0.06	61.37	0.08	0.05	34.40
13	−0.07	0.03	−0.09	0.11	0.05	71.61	0.12	0.06	56.44	0.09	0.05	27.86
16	−0.53	−0.27	−0.52	0.11	0.05	75.83	0.12	0.06	61.27	0.09	0.05	27.96
10	0.35	0.07	0.32	0.12	0.06	67.54	0.13	0.07	55.81	0.11	0.06	34.97
9	0.60.	0.16	0.49	0.15	0.07	76.35	0.16	0.08	59.37	0.13	0.07	29.50

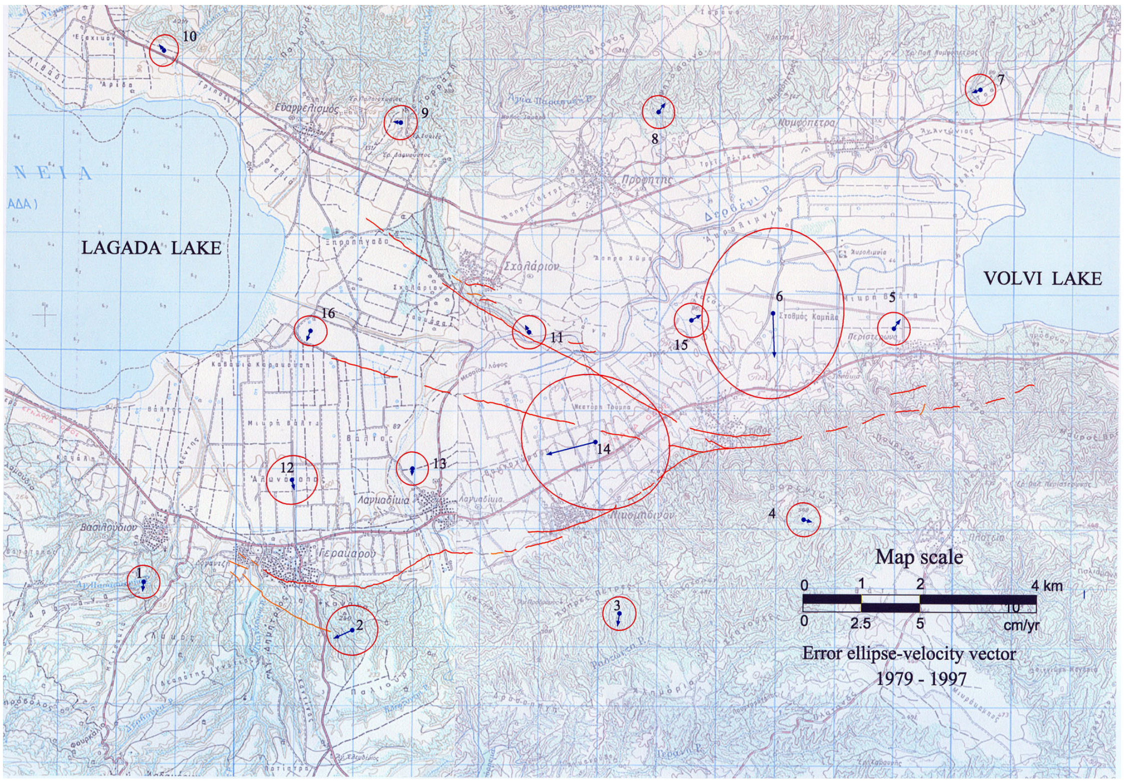

Fig 4. Velocity vectors and their confidence error ellipses (1−a=0.95) , for the Volvi Network as results from the measurements in the years 1979, 1981, 1982, 1983, 1989, 1990 (classical network) and 1995, 1997 (GPS Network).

5. Concluding remarks

The presented study is rigorously developed using certain geodetic methods and algorithmic techniques in order to detect crustal deformations. The process has been extensively applied in the geodynamically interesting area of Volvi Lake, near the city of Thessaloniki, where more than twenty years classical and GPS data are available.

The analysis shown that there is a marginal derformation in the area, a remark that is mainly enforced by the results of the deformation study by the exact collocation method.

Last years the results reflect a slight relaxation of the deforming body in terms of local geodynamic activity.

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