Chaotic behavior of new experimental data of the LTGP (2004-2006) confirm possible relation to seismic activity in Western Greece

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Abstract. Observations of the long-term geoelectric potential (LTGP) difference are presented in this paper. The data have been collected during a three-year (2004-2006) investigating period. Moreover, this paper constitutes a continuation of two previously published works with eleven-year (1993-2003) experimental data. For data logging purposes, an automatic system for collection, transfer and processing of geoelectric measurements operates at the Seismological Laboratory of the University of Patras. The analysis of these data using Lyapunov exponents and Takens estimator confirm their quite chaotic behavior. The Lyapunov exponents have also been calculated for short periods of twenty days, i.e. ten days before and ten days after the earthquakes occurred during this three-year period. By thorough examination of the resulting Lyapunov spectrums, it seems that these are subject to possible changes prior to an earthquake.

1. Introduction
Over the years many researchers have studied the correlation between the change in value of a certain physical parameter and the occurrence of an earthquake. Among the different methods under investigation, the study of anomalies in the behavior of the geoelectromagnetic field has attracted most of the attention, and over the last three decades electrical measurements over a broad frequency range have been carried out. Detected signals vary in duration pattern and have specific features and spectral characteristics. There is strong evidence that anomalous changes of the geoelectromagnetic field take place prior to strong earthquakes leading to attempts to correlate this activity with the impending
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earthquakes. Electromagnetic precursors to earthquakes have been reported by a number of researchers, raising hopes that an eventual prediction of damaging earthquakes might be possible [1]-[5].

Among the most extensive and promising reports of precursor electromagnetic signals are the observations of the long-term geoelectric potential (LTGP). The data presented in this paper have been collected during a three-year (2004-2006) independent experimental investigation at the Seismological Center of the University of Patras. These data constitute the third part of a fourteen-year (1993-2006) observation. The authors have studied and published the first part (1993-1997) and the second part (1998-2003) of the data in [6] and [7] respectively. The recorded signals are gradual variations of the electric field (GVEF), periodic variations of the electric field (PVEF) as well as seismic electric signals (SES), which are transient variations of the electrotelluric field [8].

To the authors knowledge it has not been reported before in the open literature such a large amount of data dealing with seismic activity except [6]-[7]. During the period 1993-2006 several destructive earthquakes have occurred in Western Greece, a territory with the highest seismic activity in Europe.

The analysis of the first and the second part of the data (1993-2003) [6]-[7] by means of Lyapunov exponents (LEs) has shown a quite chaotic behavior of the electric field preceding strong earthquakes in this region. The present analysis of the third part of the data (2004-2006) by means of LEs and Takens estimator confirms the previous results. The calculation of LEs for short periods of twenty days, i.e. ten days before and ten days after the earthquakes that have been occurred, reveal some interesting results concerning the change of the chaotic behavior prior to an earthquake in accordance with [6]-[7].

2. LTGP acquisition system
The measurement of the geoelectric field is relatively simple, sensing the geoelectric potential difference between pairs of electrodes, which are placed in the ground at specific locations. The current explanation of the electrical precursors includes the piezoelectric effect of quartz, contained within the rocks, and fluid flow due to the application of stress, which cause the redistribution of pore fluids.

In this system the monitoring of the geoelectric potential difference is achieved by five sets of dipoles arranged in short as well as long distances (figure 1). The acquisition system in [6] contained only four sets of dipoles. One new set has been added since 1999. These dipoles make use of Pb-PbCl₂ electrodes. Two sets have an electrode separation of 100m and are adjusted towards the N-S (ch0) and E-W (ch1) one perpendicular to each other. The third set (ch2) has an electrode separation of 300m and is directed towards the NE-SW. The fourth one has an electrode separation of 3000m in the direction NW-SE (ch4). The fifth set has an electrode separation of 500m in the direction NW-SE (ch5).

![Figure 1. LTGP acquisition system.](image)

3. Observed signals
Reported electromagnetic precursor signals appear to have a wide range of time duration, amplitude level and spectral characteristics. The continuously measured parameters of the data acquisition system are the long time variations. Long time variations are considered as anomalies of the geoelectric potential with duration of three to ten days and are observed two to four weeks prior to an earthquake occurrence. The digitization rate for observing long time variations in our station is set at 1 sample/hr. So, during the period 01/01/2004-31/08/2006 we have obtained 23376 data (points).

The geoelectric potential difference that has been monitored during the three-year investigation (2004-2006) is presented in figure 2 for channels ch0, ch1 and ch4.

![Figure 2. Geoelectric potential difference for ch0, ch1 and ch4.](image)

The major earthquakes (>4.8Ms), occurred during this period, are presented in figure 3. Table 1 gives more details about these earthquakes while figure 4 presents the exact epicenters in the area of Western Greece. The earthquakes that we have focused our attention on, are No.1 of medium magnitude and relative distant epicenter in city of Kalamata, No.3, a strong and distant one southwest of Zakynthos island in Ionio sea and No.4, a strong one in Zakynthos island. We have not considered the sequence No.6-10 in Zakynthos island because the data acquisition system was out of operation during that period.

![Figure 3. Major earthquakes (>4.8Ms) in Western Greece during the period 2004-2006.](image)

![Figure 4. Epicenters of the major earthquakes in Western Greece during the period 2004-2006.](image)

4. Confirmation of chaos in the observed signals

A chaotic system must contract in some directions and expand in others with the contraction outweighing the expansion [9]. Lyapunov exponents (LEs) [9] are used to quantity the expansion and contraction occurring in a dynamical system. The largest (dominant) LE is the most important. A
strange attractor is distinguished from other types of attractors by the existence of at least one positive LE.

**Table 1.** Major earthquakes that occurred in Western Greece during the period 2004-2006.

| No. | Date       | Time  | Depth (km) | Magnitude |
|-----|------------|-------|------------|-----------|
| 1   | 01/03/2004 | 00:35 | 14         | 5.0       |
| 2   | 05/10/2004 | 10:41 | 29         | 4.8       |
| 3   | 31/01/2005 | 01:05 | 16         | 5.7       |
| 4   | 18/10/2005 | 15:25 | 22         | 5.6       |
| 5   | 14/03/2006 | 09:16 | 19         | 4.8       |
| 6   | 03/04/2006 | 00:49 | 20         | 4.8       |
| 7   | 04/04/2006 | 22:05 | 18         | 5.2       |
| 8   | 11/04/2006 | 00:02 | 18         | 5.2       |
| 9   | 11/04/2006 | 17:29 | 18         | 5.4       |
| 10  | 15/04/2006 | 21:15 | 15         | 4.8       |
| 11  | 25/05/2006 | 23:14 | 35         | 4.8       |

In order to calculate the LEs of the experimental data, time delay reconstruction has been performed [10]. Delay reconstruction builds an n-dimensional orbit out of a time series once we select two parameters: the embedding dimension and the time delay.

Furthermore, in order to determine good settings for delay reconstruction, the autocorrelation function and mutual information function [11] are used to find a good choice of delay time, and Cao’s method [12] to find a good choice of embedding dimension.

Another way to confirm the chaotic behavior of the experimental data is the calculation of the correlation dimension by means of Takens estimator [13]. The strange attractors have in general a non-integer dimension.

The chaotic behavior of the observed signals has been confirmed by means of TSTOOL [14]. It is a software package implemented mainly in Matlab. The dominant LE and the Takens estimator have been estimated for each channel. Table 2 summarizes all the estimated dominant LEs and Takens estimators for all the cases.

**Table 2.** LEs and Takens estimator for all the channels.

| Channel | Dominant LE | Takens estimator |
|---------|-------------|------------------|
| ch0     | +4.404      | 1.6761           |
| ch1     | +4.701      | 0.5059           |
| ch2     | +4.412      | 0.3522           |
| ch4     | +4.177      | 1.2616           |
| ch5     | +4.462      | 2.1495           |

The results from table 2 verify the fact that all the signals from all the channels are quite chaotic, as they have a positive dominant LE and a non-integer Takens estimator in accordance with [6]-[7].

5. **Changes of chaotic behavior of the observed signals and results**

With the purpose of investigating in detail the eventual relation between the changes of chaotic behavior of the observed signals and the corresponding earthquakes, dominant LEs have been estimated for many different short periods prior to and after the occurrence of each earthquake. The estimations presented here are for short periods of 24 hours, ten days before and ten days after the occurrence of earthquake. The average of the dominant LEs, as well as the median of them,
considering three channels (ch0, ch1 and ch4), have been calculated. The estimated dominant LEs as well as the average and median dominant LEs are plotted in figures 5-7.

**Figure 5.** Dominant, average and median dominant LEs ten days before and ten days after earthquake No. 1

**Figure 6.** Dominant, average and median dominant LEs ten days before and ten days after earthquake No. 3

**Figure 7.** Dominant, average and median dominant LEs ten days before and ten days after earthquake No. 4

In [6]-[7], it was concluded that strong earthquakes, with close epicenter to the observation station, present an increasing fluctuation of the LE values before the occurrence of the earthquake, while after the earthquake these values diminish. The present work demonstrates similar results.
The results presented in figure 6 show an increase of the chaotic behavior with simultaneous occurrence of a maximum prior to strong earthquake No. 3 in Ionio sea. Right after the earthquake a significant decrease of LE values tending to zero is observed. In this case the LE values vary significantly before and after the earthquake. Similar results appear in figure 7 for the earthquake in Zakynthos island. These two cases reveal that a significant variation of the chaotic behavior of the LTGP can be observed in strong earthquakes with relatively small distance of the epicenter from the acquisition station. More specifically, the LEs decrease from high positive values to low values tending to zero after the earthquake.

For the medium magnitude earthquake No.1 in city of Kalamata, that had a distant epicenter, the results were different.

6. Conclusion

The variation of the chaotic behavior observed in geoelectrical signals, can be associated with the underlying earthquake generation mechanisms, which are also chaotic due to the evolution of the earth’s crust towards the self-organization at the critical point and involves the formation of fractal structures in the fault zone [15].

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