Physics and Chemistry of the Earth 85–86 (2015) 9–16

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

# TEC variations over the Mediterranean before and during the strong earthquake ($M = 6.5$) of 12th October 2013 in Crete, Greece

M.E. Contadakis [a], D.N. Arabelos [a,*], G. Vergos [a], S.D. Spatalas [a], M. Skordilis [b]

[a] Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Greece
[b] Department of Geophysics, Aristotle University of Thessaloniki, Greece

ARTICLE INFO

*Article history:*
Received 16 August 2014
Received in revised form 9 March 2015
Accepted 23 March 2015
Available online 16 April 2015

*Keywords:*
GPS network
Ionospheric total electron content
Wavelet analysis
Fourier transform

ABSTRACT

In this paper, the total electron content (TEC) data from eight global positioning system (GPS) stations of the EUREF network, provided by IONOLAB (Turkey), were analyzed using discrete Fourier analysis to investigate the TEC variations over the Mediterranean before and during the strong earthquake of 12th October 2013, which occurred west of Crete, Greece. In accordance with the results of similar analyses in the area, the main conclusions of this study are the following: (a) TEC oscillations in a broad range of frequencies occur randomly over an area of several hundred km from the earthquake and (b) high frequency oscillations ($f \geqslant 0.0003$ Hz, periods $T \leqslant 60$ m) may point to the location of the earthquake with questionable accuracy. The fractal characteristics of the frequency distribution may point to the locus of the earthquake with higher accuracy. We conclude that the lithosphere–atmosphere–ionosphere coupling (LAIC) mechanism through acoustic or gravity waves could explain this phenomenology.


## 1. Introduction

It is generally accepted that tectonic activity resulting in earthquakes induces variations in Earth's ionosphere through the so-called lithosphere–atmosphere–ionosphere mechanism (LAIC) (Molchanov et al., 2004; Molhavov and Hayakawa, 2008; Korepanov et al., 2008). This consensus emerged from the results of a great amount of research through ground-based experiments (Molchanov et al., 2004, 2005; Rozhnoi et al., 2004, 2009; Biagi et al., 2009; Hayakawa et al., 2013), space-borne studies (Parrot et al., 2006; Hayakawa et al., 2000) and combined space-borne and ground-based studies (Rozhnoi et al., 2007; Muto et al., 2008; Boudjada et al., 2013). Finally, the development of GPS and GLONASS satellite systems provided a perfect opportunity for simultaneous investigation of TEC variations over a great number of locations around the earth and furthermore, for investigation of any relationship between these variations or isolated variations of TEC which may occur over a particular site with enhanced tectonic activity. Much work has also been done in this area (e.g., Afraimovich et al., 2001, 2002; Akhoondzadeh et al., 2010, 2012; Contadakis et al., 2008, 2012a,b). These studies indicated that, over a broad area where a strong earthquake occurs (magnitude >5.5), uneven variations in TEC are observed. Recently some researchers have criticized the idea of ionospheric precursors to earthquakes as it has been deduced from data with low accuracy and resolution in conditions of moderate geomagnetic activity (Afraimovich et al., 2004; Dautermann et al., 2007; Thomas et al., 2012; Masci, 2013). Therefore, in our analysis we use TEC estimations with high resolution (TEC estimations from IONOLAB with resolution of 2.5 min) and we exclude the days of moderate and high geomagnetic and solar activity. In addition, we compensate for the effect of minor solar activity by comparing the real time TEC estimation with the mean TEC estimation for the sixteen days of our study, which has a contribution from solar activity. In this paper the total electron content (TEC) data from eight global positioning system (GPS) stations of the EUREF network (http://www.epncb.oma.be), provided by IONOLAB (http://www.ionolab.org), were analyzed using fast Fourier transform analysis to investigate the TEC variations over the Mediterranean before and during the seismic activity that occurred on the 12th of October, 2013 west of Chanea of Crete, Greece.

## 2. The seismic activity west of Chanea in October of 2013

The Hellenic Arc, the margin along which the collision between the Eurasian and the Mediterranean plates occurs, is dominated by low-angle thrust faults. This thrust-fault zone, following the Hellenic trench, is located at the south western part of this margin

* Corresponding author. Tel.: +30 2310996091; fax: +30 2310996408.
*E-mail addresses:* kodadaki@vergina.eng.auth.gr (M.E. Contadakis), arab@eng.auth.gr (D.N. Arabelos), vergos@topo.auth.gr (G. Vergos), sspatala@topo.auth.gr (S.D. Spatalas), manolis@geo.auth.gr (M. Skordilis).

http://dx.doi.org/10.1016/j.pce.2015.03.010
1474-7065/

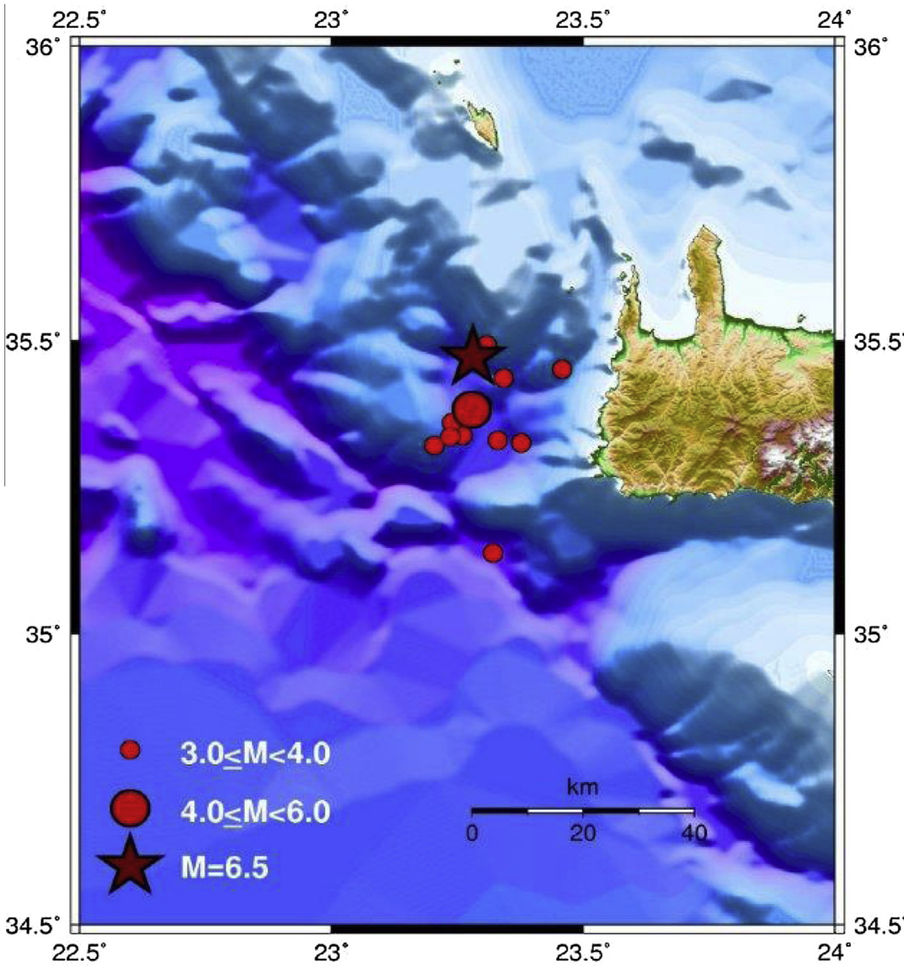


**Fig. 1.** Geographical distribution of the aftershocks that occurred during the 1st week of the sequence. The main shock on October 12, 2013 with an $M = 6.5$ is denoted by a star.

(Papazachos and Delibasis, 1969). The faults of this zone are oriented NW-SE and dip to the NE (i.e., toward the concave side of the arc (Aegean)) and are responsible for the generation of strong, mostly shallow, earthquakes. The earthquake of October 12, 2013, $M = 6.5$ (Fig. 1) was generated by a thrust fault striking NW-SE with a right-lateral component (az = 340°, dip = 3°, rake = 130° according to GCMT). The seismic fault is relatively shallow at the early stage of the formation of the Wadati–Benioff zone (Papazachos and Comninakis, 1970, 1971; Papazachos et al., 2000). Table 1 displays the parameters of the main shock and the aftershocks which occurred within the first week of the sequence (12–19 October 2013) (quoted from the on-line monthly bulletins from the Department of Geophysics, University of Thessaloniki, http://geophysics.geo.auth.gr/the_seisnet/WEBSITE_2005/station_index_en.html)) (Table 1). The magnitude of the mainshock ($M = 6.5$) was derived by considering all of the available information from national and international sources.

## 3. The data

### 3.1. TEC values

In this paper, we investigate the variation in TEC over the Mediterranean before and during the seismic activity on the 12th of October; thus, we use the TEC estimates provided by IONOLAB (http://www.ionolab.org) (Arikan et al., 2009) for the time period between 28/09/2013 and 15/10/2013 from eight mid-latitude GPS stations from EUREF; these stations cover distances from the active area ranging from 650 km to 2500 km. The selected GPS stations are at approximately the same latitude and are expected to be affected equally from the equatorial anomaly as well as from auroral storms.

Table 2 displays the eight EUREF station used in this study, while Fig. 2 displays the locations of the eight GPS stations and the main shock. The IONOLAB TEC estimation system uses a single station receiver bias estimation algorithm, IONOLAB-BIAS, to obtain daily and monthly averages of receiver bias and is successfully applied to both quiet and disturbed ionosphere days for a station at any latitude. In addition, TEC estimations with high resolution are also possible (Arikan et al., 2008). The IONOLAB system provides comparisons of its TEC estimations with the estimations of the other TEC providers of IGS on its site. In this work, only TEC estimations in perfect accordance between all providers were used. The TEC values are given in the form of a time series with a sampling gap (resolution) of 2.5 min.

### 3.2. Geomagnetic and solar activity indices

The variations of the geomagnetic field were followed by the Dst-index and the planetary kp three hour indices quoted from the Space Magnetism Faculty of Science, Kyoto University site (http://swdcwww.kugi.kyoto-u.ac.jp/index.html) for the time period of our study. Fig. 3 displays the Dst-index variations in