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Total electron content variations in the ionosphere before the Colima, Mexico, earthquake of 21 January 2003

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RESUMEN

En la actualidad se encuentra bien establecida la existencia de variaciones ionosféricas anómalas asociadas con el proceso de preparación de sismos fuertes (M>5). Con el fin de comprobar posibles variaciones ionosféricas que estuvieran relacionadas con el reciente temblor de Colima, México, M=7.8, del 21 de enero de 2003, se analizaron los datos de 5 receptores GPS de la red del Instituto Nacional de Geografía, Estadística e Informática (INEGI) de México. Se encontró que el TEC obtenido a partir de estos datos muestra anomalías importantes de dos a tres días antes del impacto sísmico, mientras que el coeficiente diario de correlación cruzada calculado para diferentes pares de receptores GPS presenta una caída importante dentro de un intervalo de uno a cinco días antes de dicho impacto. Por otra parte, la distribución horizontal (latitud-longitud) de las desviaciones del TEC con respecto a la media mensual para el día y la hora del sismo tuvo su máximo en un punto cercano a la proyección vertical en la ionosfera del epicentro del mismo. Hemos concluido a partir de esto que las variaciones observadas en la ionosfera durante el proceso de preparación y de realización del sismo pueden ser consideradas como posibles precursores de corto plazo del mismo.

PALABRAS CLAVE: Contenido total de electrones, variaciones ionosféricas, precursor sísmico.

ABSTRACT

Anomalous ionospheric variations associated with the process of strong earthquake (M>5) preparation has been fairly well established. To check possible ionospheric variations connected with the recent Colima earthquake, M=7.8, of 21 January 2003, the data of five stationary GPS receivers of the National Institute of Statistics, Geography and Informatics (INEGI) of Mexico network were analyzed. It was found that the vertical total electron content showed anomalies two to three days before the seismic shock, while the daily cross correlation coefficient calculated for the different pairs of GPS receivers presented a drop within an interval of one to five days before the seismic shock. Also, the horizontal spatial (latitude-longitude) distribution of the TEC deviation had its peak of deviation in a point close to the vertical projection on the ionosphere of the impending earthquake epicenter, thus revealing the local character of the observed anomaly. We conclude, that the observed variations in the ionosphere can be regarded as a possible short-term earthquake precursors.

KEY WORDS: Total electron content, ionosphere variations, precursor.

1. INTRODUCTION

Seismo-ionospheric coupling is a fast developing multidisciplinary area involving more and more scientists in different countries (Hayakawa and Molchanov, 2002; Pulinets and Boyarchuk, 2004). The coupling occurs when an anomalous electric field from the ground surface penetrates into the ionosphere (Pulinets *et al*., 2000). The ionizing process due to radon action in the near-ground layer of the atmosphere may be responsible for the generation of this anomalous electric field (Boyarchuk *et al*., 1998). Anomalous ionospheric variations associated with the earthquake preparation have been registered using different techniques of ionosphere monitoring, such as ground based vertical sounding (Liu *et al*., 2000), topside vertical satellite sounding (Pulinets and Legen'ka, 2003), and GPS TEC measurements (Liu *et al*., 2004). Identification of the anomalous ionospheric variations associated with the earthquake preparation is possible on the basis of their morphological characteristics (Pulinets *et al*., 2003a). The PREVENTION project in Mexico is aimed at establishing the infrastructure of geophysical measurements and to provide an experimental basis for studies of seismo-ionospheric coupling and for the practical application of the obtained results (Pulinets *et al*., 2004a). A network of stationary GPS receivers has been installed with the purpose of obtaining information on ionospheric variations over Mexico, as a first step to develop of technology of data processing and visualization. At the same time, by collecting information for further statistical analysis, we have checked ionosphere variations around the time of recent strong earthquakes in Mexico, such as the Colima earthquake of 21 January 2003.

2. THE COLIMA EARTHQUAKE

The 2003 Colima (Tecomán) earthquake occurred near the juncture of three tectonic plates: the North American plate to the northeast, the Rivera plate to the northwest, and the

Cocos plate to the south. Both the Rivera plate and the Cocos plate are being subducted beneath the North American plate (Bandy *et al*., 2000). The event filled a seismic gap located between the rupture zones of the M_w 8.0 1995 Manzanillo earthquake and the M_w 7.6 earthquake of 1973 (Singh *et al*. 2003). Different agencies give different locations of the hypocenter and the focal mechanisms, as well as different earthquake magnitudes (from 7.4 to 7.8). For the epicenter location, we will use the determination of the National Seismological Service (SSN) of Mexico which is 18.22 N and 104.60 W. The main shock took place at 2006 LT of 21 January, which correspond to 0206 of 22 January GMT.

3. GPS DATA

The principles and technology of vertical TEC determination from GPS data may be found in the literature (Sardon *et al*., 1994; Ciraolo *et al*., 1997; Liu *et al*., 2004). Because of wide spread of GPS technology all over the world, it starts to replace the traditional vertical sounding of the ionosphere by ionosondes. The correlation coefficient of the vertical TEC with measurements of the critical frequency of the ionosphere obtained by ionosonde is near 0.93, see for example. (Liu *et al*., 2004). The critical frequency *foF2* is the maximal ordinary mode frequency reflected from the ionosphere during vertical sounding and is proportional to the square root of the peak electron concentration in the main maximum of the ionosphere, $NmF2 = (foF2)^2/80.3$ (Davies, 1990). Statistical analysis made for the Taiwan seismic zone has determined anomalies in GPS TEC for strong earthquakes (M>6) within five days before the seismic shock (Liu *et al*., 2004).

A network of five permanent GPS receivers of INEGI detected differences in the ionospheric variations around the time of Colima earthquake. The receivers were close to the earthquake epicenter, as shown in Table 1.

Table 1

Coordinates of INEGI GPS receivers used in analysis

Station	Latitude	Longitude (W)
COL2	19.244	103.702
CUL1	24.799	107.384
INEG	21.856	102.284
MEXI	32.633	115.476
TOL2	19.293	99.643

4. IONOSPHERIC VARIATIONS OVER MEXICO AND EQUATORIAL ANOMALY

The ionosphere structure greatly varies with latitude, especially in areas located at high latitudes and in the region of the equatorial anomaly (Ondoh and Marubashi, 2001). The equatorial anomaly is formed at both sides of the geomagnetic equator in the form of peaks of electron concentration at latitude spacing of 10° - 15° away from the geomagnetic equator. These peaks are driven by the east-directed electric field at the geomagnetic equator appearing in afternoon hours. The ionospheric plasma drifts upward in crossed eastward electric and horizontal (at geomagnetic equator) geomagnetic fields. The plasma drifts up and then slides down on both sides of the geomagnetic equator forming the peaks called crests of equatorial anomaly. The eastward electric field appears only in the afternoon, and that is the reason why the maximum development of equatorial anomaly is reached at that time of the day. In quiet geomagnetic conditions, the electric field variations are very regular in local time; thus the equatorial anomaly peaks appear at practically the same time every day. The morphology of the equatorial anomaly has been studied by many authors. Recent publications using the ionospheric tomography, GPS TEC and the topside sounding techniques can be found in Andreeva *et al*. (2000), Franke *et al*. (2003), and Pulinets *et al*. (2003b). All these studies show that the maximum development of the equatorial anomaly crests takes place at 14-15 LT (depending on the season). So the appearance of any peaks comparable in amplitude with the maximum afternoon value during quiet geomagnetic conditions at other intervals of local time may be regarded as anomalous and one should seek for an additional source to explain it.

Figure 1 shows the latitudinal configuration of the ionosphere obtained with the topside sounder of the Soviet Intercosmos-19 satellite. Mexico is situated at the slump of the northern crest of the equatorial anomaly, and one can expect the very regular, daily variations of the electron concentration over Mexico, especially as concerns to the local time of the main daily peak.

5. VERTICAL TEC VARIATIONS AT COLIMA STATION

The standard procedure used in ionospheric studies was applied to our GPS records (Ciraolo and Spalla, 1997): the vTEC values were derived form the GPS data of January 2003 and the deviation of the current measurement from the monthly mean for the ionospheric variability estimation obtained as

$$\Delta TEC(\%) = \frac{100 \cdot (TEC - M)}{M} ,$$

where M is the monthly mean.

The variations of the vTEC for January 2003 observed at the Colima receiver are presented in the top panel of Figure 2a, while in the lower panel the planetary equatorial Dst index, indicating the level of geomagnetic activity, is shown.

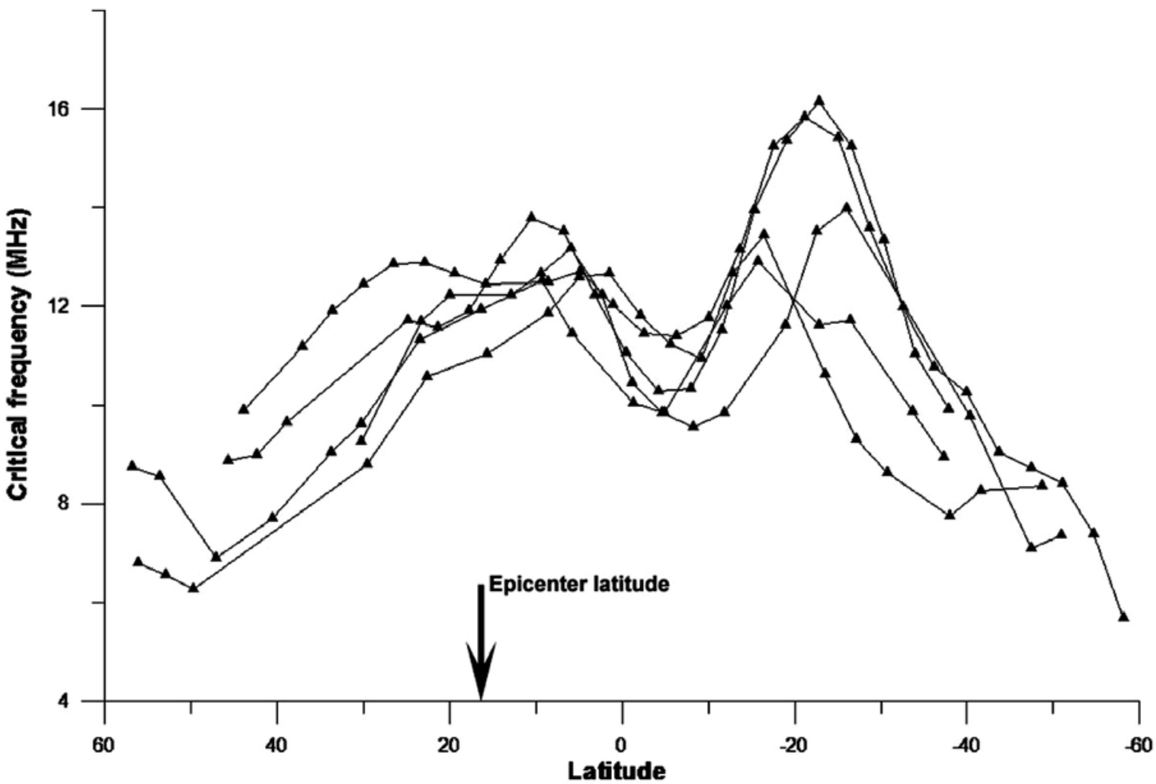

Fig. 1. Critical frequency *foF2* scaled from topside ionograms of Intercosmos-19 satellite passing over Mexico.

The common feature of the observed variations is the vTEC increase after the appearance of negative peaks of Dst, which indicates ionosphere reaction to small magnetic storms. For a better temporal resolution, only one week of variations around the time of the Colima earthquake is presented in Figure 2b. Points indicate the time series for the vTEC derived from the Colima receiver data. The interruption on 21 of January is due to a power outage during the seismic shock. The continuous black line represents the calculated monthly mean M, and the grey lines are the upper and lower bounds $M + \sigma$, and $M - \sigma$ where σ is the standard deviation. It can be seen that all the data from the time series for the presented time interval is below the upper bound except on days 18 and 19 of January. And if the maximum on 19 of January can be attributed to the geomagnetic disturbance shown in Figure 2a, the additional peak at 1010 LT on 18 of January can be regarded as anomalous according to the discussion in Section 4. The nature of this anomaly and its possible relation with the earthquake occurred on 22 January is discussed lower.

6. PRECURSORY VARIATIONS IDENTIFICATION

Studies of the ionospheric variations associated with earthquake preparation suggest the existence of certain morphological features of especial interest for this study (Pulinets *et al*., 2003), among which stands out the local character of the processes that take place in the ionosphere in connection with the earthquake. It has been found that the modified area in the ionosphere is tied to the seismoactive area or, more precisely, to the area of the earthquake preparation, and its size depends on the magnitude of the impending earthquake (Pulinets and Boyarchuk, 2004). So, if we are able to build a map of electron concentration distribution over a seismoactive area, we should detect the irregularity possibly associated with the position of the epicenter of an impending earthquake. The local character of the seismo-ionospheric variations makes it possible to identify them by differentiation from other ionospheric variations occurring during geomagnetic disturbances which, as it is well known, have a global character. The strong geomagnetic control of the ionosphere during magnetic storms makes variations in the ionosphere synchronous at the neighboring stations, up to distances of about 700 km. As a result of this, the correlation between the stations will be high during geomagnetic perturbed conditions, even for high absolute amplitude variations, in comparison with lower amplitude variations before earthquake (Pulinets *et al*., 2005a). This feature of the ionosphere behavior was used to develop the correlation analysis technique for the ionospheric precursors identification (Pulinets *et al*., 2004b).

In most recent studies (Pulinets *et al*., 2005) a new index, based on a multiparameter analysis, was developed in order to characterize the ionospheric variability associated

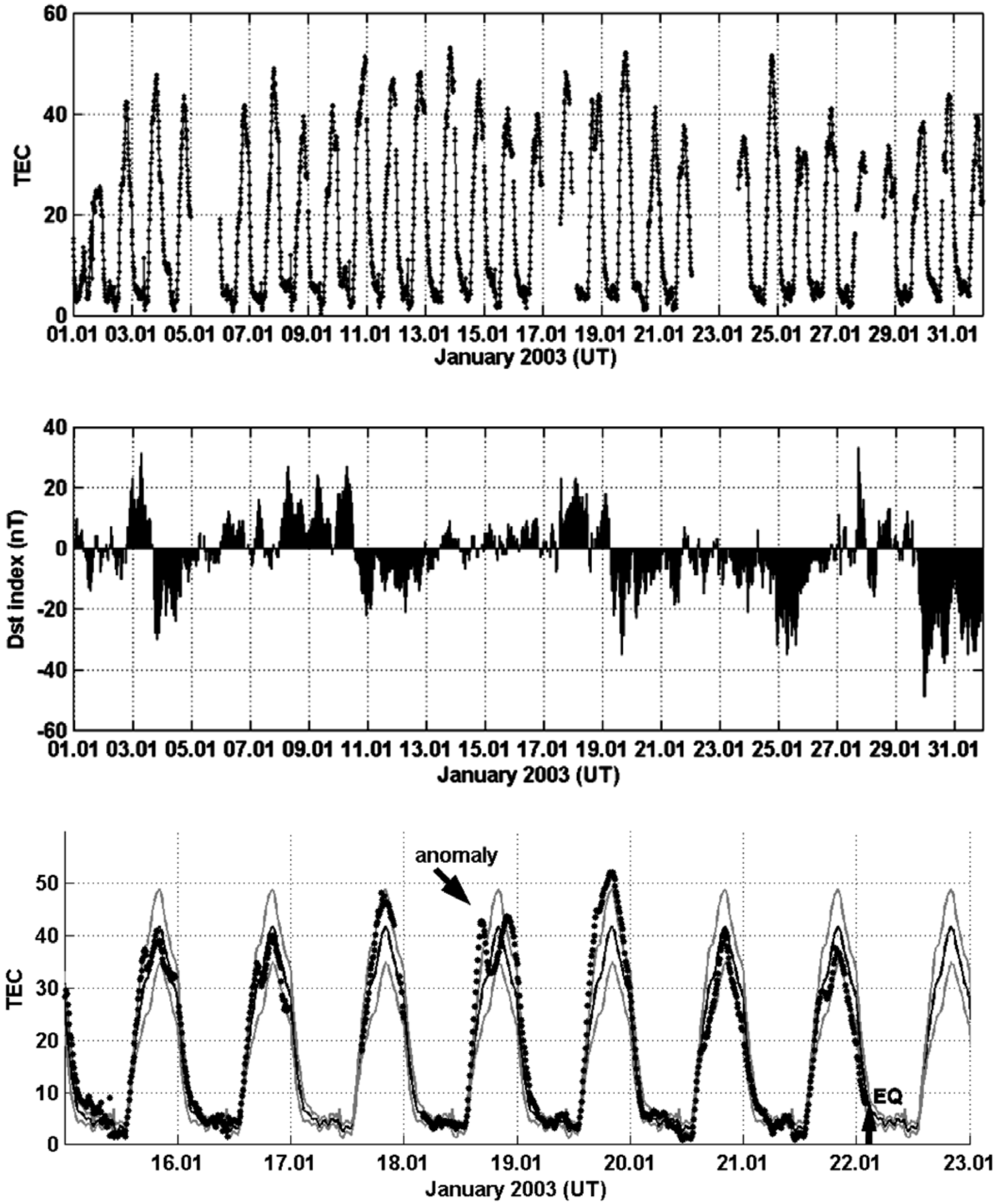

Fig. 2. a) – upper panel time series for January 2003 of GPS TEC derived from the data of Colima GPS receiver, bottom panel – global equatorial Dst index variations for January 2003. b) -Vertical TEC variations (points) in comparison with the monthly mean *M* (continuous black line). Grey lines – upper and lower bounds calculated as $M + \sigma$ and $M - \sigma$ respectively.

with the seismic activity. It is well known that different types of precursors are observed before strong earthquakes (Lomnitz, 1994). Pulinets and Boyarchuk (2004) incorporated most of them in the complex model of Lithosphere – Atmosphere – Ionosphere (LAI) Coupling, demonstrating their common nature. One of the most important precursors which has recently attracted the attention of many scientists all over the world is the latent heat anomaly observed before the earthquakes (Dey and Singh, 2003). As air ionization by radon is the common source of both the latent heat and ionospheric anomalies (Pulinets and Boyarchuk, 2004), we think they should be observed synchronously with the aim to use them as another check for the determination of ionospheric precursors.

6.1 Correlation technique

We calculated the daily cross-correlation coefficients for pairs of receivers from Table 1 in the following form

$$C = \frac{\sum_{i=0,k}(f_{1,i} - af_1)(f_{2,i} - af_2)}{k(\sigma_1\sigma_2)},$$

where indices *1* and *2* correspond to the first and second receivers, *f* is the value of the vTEC calculated for every 10 minutes, $k = 143$ (144 values of TEC per day), and *af* and σ are determined by the following expressions:

$$af = \frac{\sum_{i=0,k} f_i}{k+1}$$

$$\sigma^2 = \frac{\sum_{i=0,k}(f_i - af)^2}{k},$$

where *af* is the daily mean value of the TEC, and σ is the standard deviation.

The COL2 receiver (the closest to the epicenter) suffered power outage after the earthquake and stopped operating for one day (Figure 2). Therefore the Toluca receiver (TOL2) was defined as the reference station. In Figure 3 the cross-correlation coefficients are presented for (from top to bottom): Toluca-Culiacán, Toluca-Aguascalients and Aguascalientes-Culiacán. Notice the drop of the correlation coefficient five days before the seismic shock in the two upper panels and practically no drop in the lower one, indicating that the ionosphere over Toluca –which is closer to the epicenter– was more variable several days before the seismic shock, as it has been found in previous publications (Pulinets *et al*., 2004b). The maximum local variability was reached between 17 and 18 January. Ionospheric variations over Aguascalientes and Culiacán were almost synchronous, hence the high values of the daily cross-correlation coefficient (bottom panel of Figure 3). It means that the anomaly developed on 17-18 of January close to the epicenter was the result of a process of local character.

6.2 Index of seismo-ionospheric variability

It was discovered recently (Pulinets *et al*., 2005a) using the GPS TEC data for the periods of strong earthquakes in California (Hector Mine earthquake M7 on October 16 of 1999, San Simeon M6.5 earthquake on December 23 of 2003, Parkfield M6 earthquake on September 28 of 2004) that the ionosphere variability increases locally within the earthquake preparation area a few days before the seismic shock. The developed index is the difference between the maximum and minimum values at any given moment of the measurements for the set of GPS receivers used for the analysis. The same technology was applied for the GPS TEC dataset of INEGI GPS receivers (Table 1) and results of calculation are presented in Figure 4. The peak of the variability is clearly observed on 18 of January (4 days before the seismic shock), and an increase of the variability starts more than one week before the seismic shock when the geomagnetic activity (see Figure 2a) is minimal. Here it should be noticed that the variability peak is observed at the same day as the anomaly shown in Figure 2b.

6.3 Anomalous latent heat flux and ionospheric anomaly

Dey and Singh (2003), using remote sensing satellite data, calculated the anomalous heat flux before several recent strong earthquakes all over the world, including the Colima earthquake of 2003 (proper description of the applied technology can be found in their publication). Here, we will draw a comparison of their latent heat calculations with our ionospheric variations at Colima station as shown in Figure 2. Dey and Singh calculated the variations of the latent heat flux over Colima for the whole year of 2003 and found the anomalous maximum on January 18, 2003 (Figure 5). The coincidence between the ionospheric anomaly (Figure 2b) and the latent heat anomaly (Figure 5) is not "by the case" as it can be explained within the frame of the LAI model (Pulinets and Boyarchuk, 2004) and by the recently developed more detailed mechanism of thermal anomalies observed before earthquakes (Pulinets *et al*., 2005b).

6.4 Spatial distribution of the ionospheric anomaly

All analyses presented in sections 6.1-6.3 indicate that January 18 was the most anomalous day, and the peak indicated in Figure 2b is not a "by the case" anomaly. In analysis of seismo-ionospheric variations the mapping is always the decisive check showing the connection of the observed

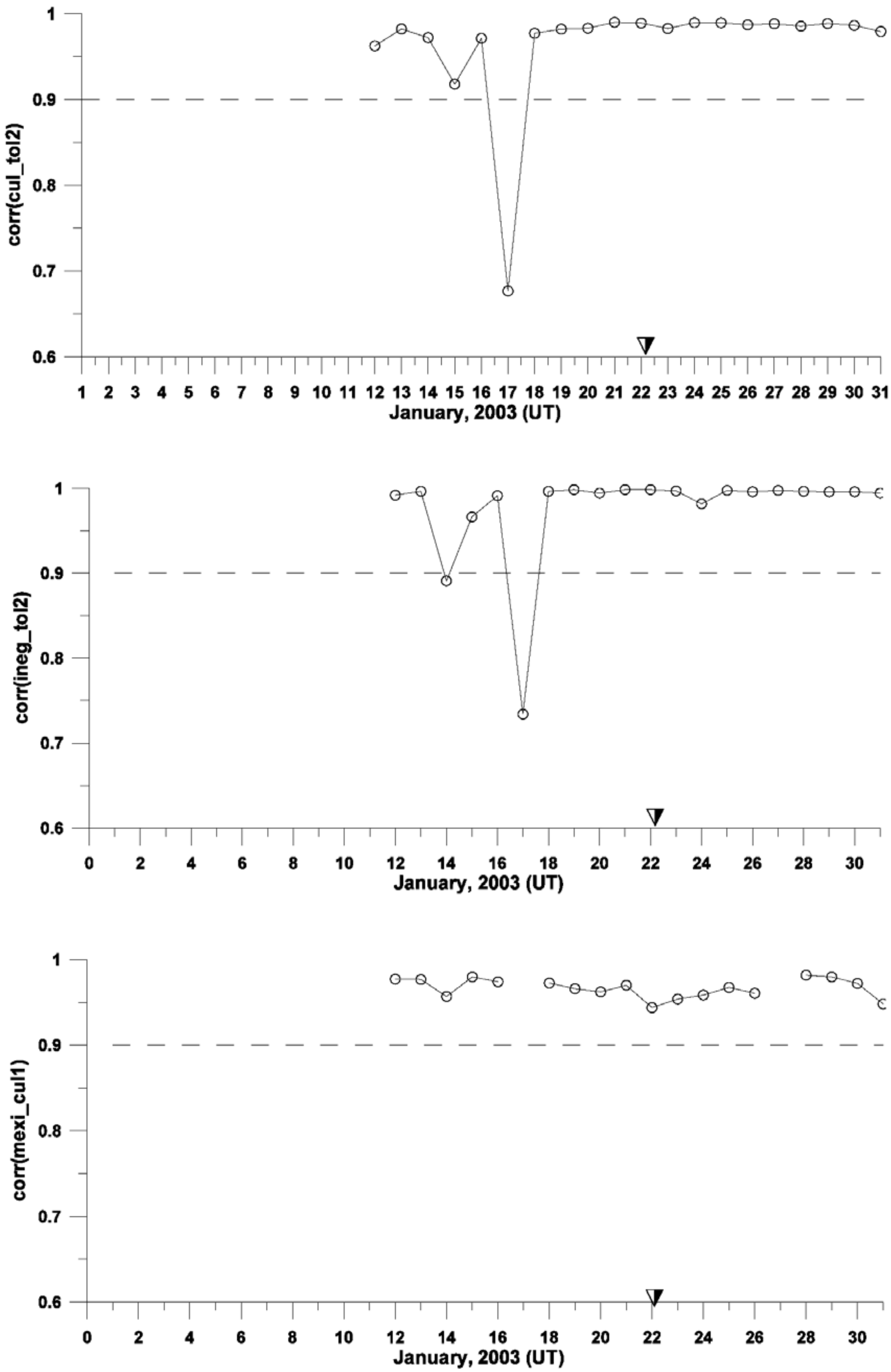

Fig. 3. Daily cross correlation coefficients calculated for the pairs of GPS receivers. From top to bottom Culiacan – Toluca, Aguascalients-Toluca, Culiacán –Aguascalientes.

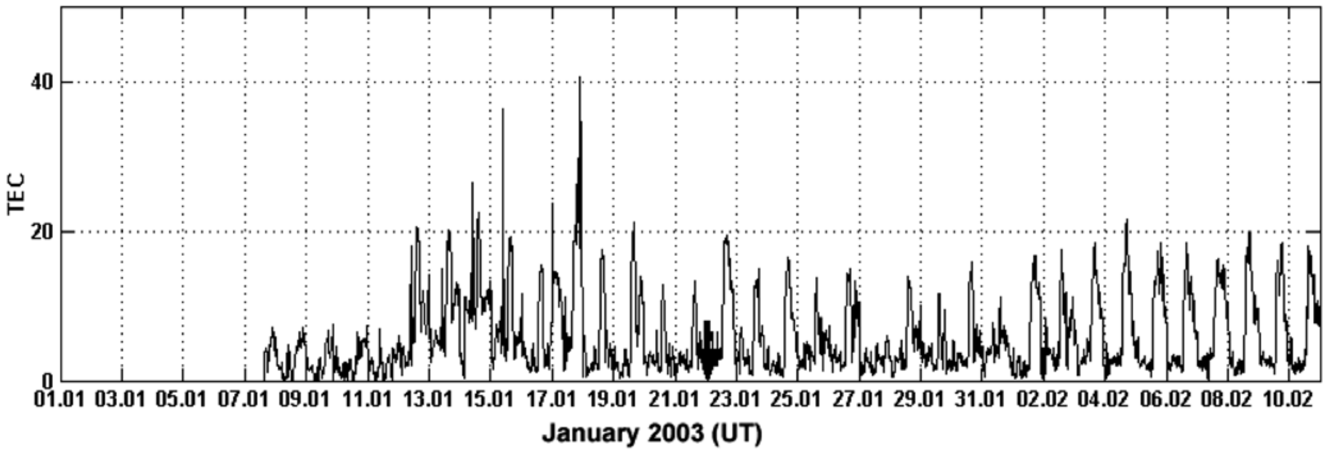

Fig. 4. Index of local ionospheric variability for January 2003 calculated from the data of GPS receivers (Table)

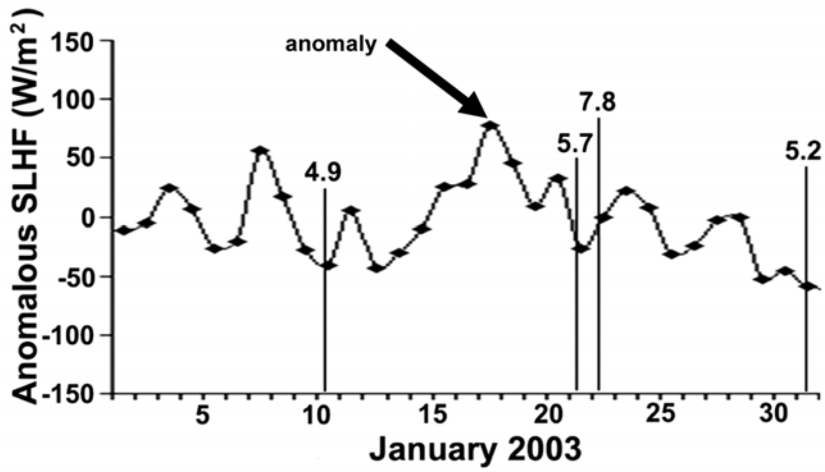

Fig. 5. Anomalous latent heat flux over Colima earthquake epicenter derived from the satellite remote sensing data for January 2003

anomaly with the position of the epicenter of impending earthquake. And it is natural to select the moment when the maximum anomaly was observed on 18 of January for the map construction. For this time the value of the DTEC (TEC deviation from the monthly mean) was calculated for all 5 stations. The obtained spatial distribution of DTEC is shown in Figure 6. The GPS receiver positions are shown as white stars, and the epicenter by a black asterisk. The peak of the anomaly was found just over the epicenter of the impending earthquake.

7. CONCLUSIONS

Anomalous variations of TEC derived from the records of GPS permanent receivers were detected within seven days before the Colima earthquake of 21 January 2003. The first minimum of the cross-correlation coefficient appeared on 14 January. These variations were detected in the time series of stations closest to the epicenter of the earthquake by correlation analysis for pairs of receivers of INEGI network, by index of local ionospheric variability and by the spatial distribution of deviation of TEC from the monthly mean. The detected anomaly coincides in time with the anomaly of the latent heat flux calculated from the satellite remote sensing data. The detected anomaly has local character, and its maximum is situated over the epicenter of the earthquake. From the correlation analysis we find that it appears one week before the seismic shock, reaches its maximum 3 days before the earthquake, and disappears after the seismic shock. By its parameters it satisfies all criteria of ionospheric precursors of earthquakes described in Pulinets *et al*. (2003) and Pulinets and Boyarchuk (2004). We conclude with high level of probability that the observed anomaly was a real precursor of the 21 January 2003 Colima earthquake, detected on the basis of the local character of the ionospheric variations associated with the earthquake preparation process, and with the help of multiparameter analysis.

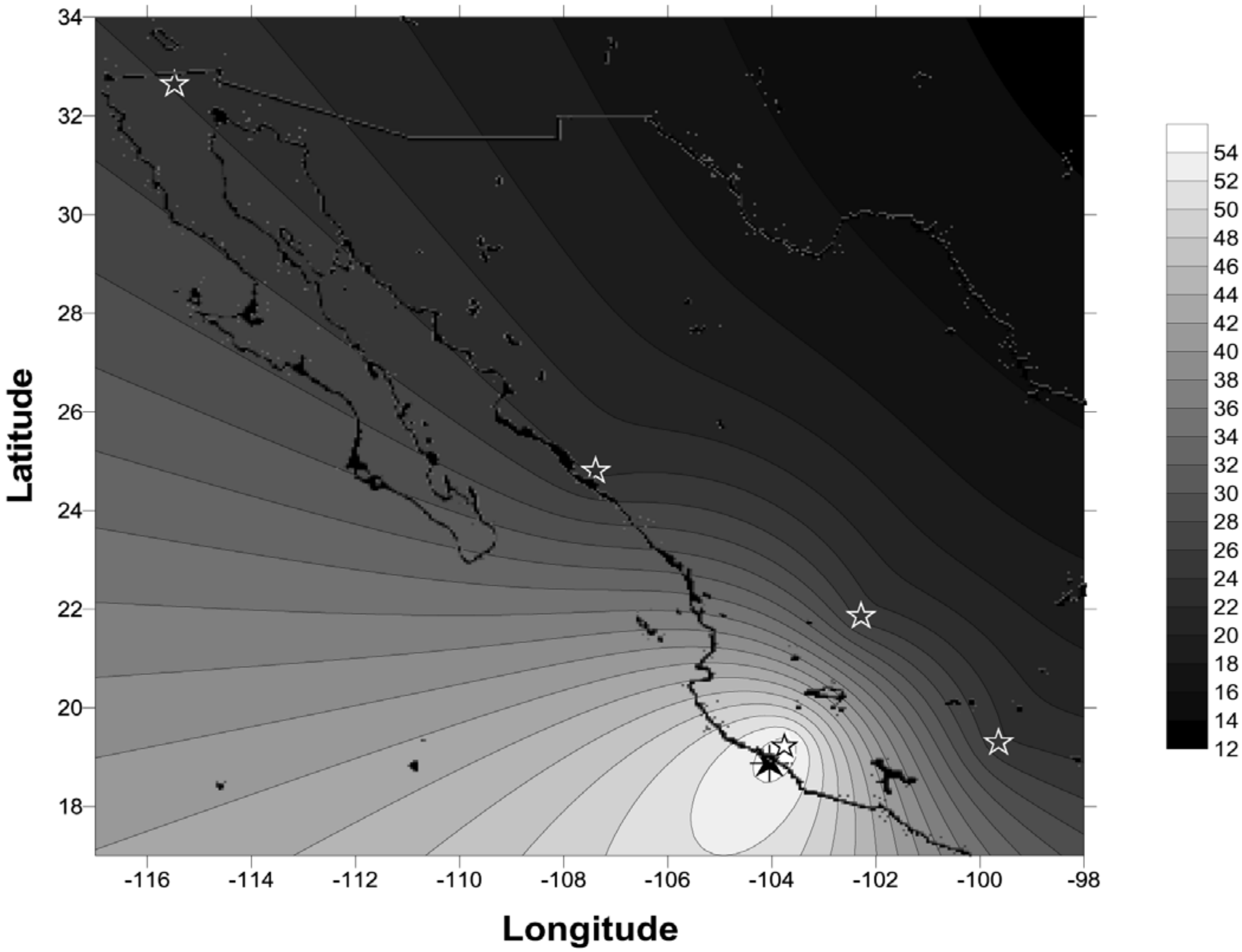

Fig. 6. Spatial distribution of ΔTEC obtained from the data of INEGI GPS receivers network for 1010 LT 18 of January 2003.

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