New Ionosphere Variability Index and its Anomaly Variation Related to Major Earthquakes Occurred in California, USA and Mexico

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Abstract

The problem of ionospheric variability is regarded from the point of view of spatial and temporal correlation between the GPS TEC variations derived from the neighbor GPS receivers records. It is demonstrated that the technique of the spatial correlation coefficient developed earlier to reveal the ionospheric variations induced by seismic activity sometimes fails. The new index of the local ionospheric variability is proposed describing the spread of GPS TEC within the given area. It is tested for periods of geomagnetic disturbances and periods of several days preceding the strong (M $\geq$ 6) earthquakes happened within the area of GPS receiver's network. It is shown that the new index is a good indicator of the earthquake preparation process, it increases few (3-7) days before the seismic shocks and comes to the normal state after the earthquake. During the periods of increased geomagnetic activity the index does mot show such variability.

1 Introduction

Day-to-day ionospheric variability is still not well established subject of the ionospheric physics. Attempts to classify the terminology of ionospheric variability one can find in the review [1]. Usually the parameter variability is expressed as a deviation (in %) from the mean or median value. One can find the quantitative estimations of the ionosphere variability in the works [2, 3, 4], showing that day-to day variability of the critical frequency foF2 lies within the limits 10-30%. The effect on the ionosphere from below is regarded as a main source of the day-to-day variability and it is demonstrated in reviews [5, 6]. Author [7] proposed the effects of seismic activity through the electromagnetic coupling with the ionosphere as one of the sources of the ionospheric variability. The detailed aspects of the physical mechanism and main morphological features of the ionospheric variability associated with seismic activity are described in monograph [8].

In the modern applications (for example navigation with GPS system), the correlation radius of the ionosphere is very important parameter [9]. But the correlation model developed by Hansen et al., does not take into account the nature of the ionosphere variability source. The present paper intends to demonstrate that the ionospheric variability character is different for different sources of this variability.

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2 The problem formulation

The ionospheric variability given by Total Electron Content (TEC) is studied in relation to the 4 major earthquakes (EQs) occurred in California (Hector Mine M 7.1, 1999, San Simeon M 6.5, 2003 and Parkfield M 6.0, 2004 see Table 1 for details), USA and Mexico (Colima M 7.6, 2003). The idea to use the correlation between the neighbor ionospheric stations to reveal the seismogenic variations in sporadic E-layer of the ionosphere was proposed in [10] and reviewed in [11]. The similar technique for the F-layer parameters of the ionosphere was developed in [12]. This technique was extended for the GPS TEC measurements [13]. To determine the radius of correlation associated with the seismic activity the conception of the earthquake preparation zone was used. It is supposed that ionospheric variability associated with seismic activity will be observed over the earthquake preparation zone [14]:

$$\rho = 10^{0.43M} \text{ km} \tag{1}$$

where ρ is the radius of the earthquake preparation zone, and M the earthquake magnitude.

Table 1. Parameters of the earthquakes and observed behavior of the ionosphere variability index

Earthquake name	Coordinates, depth	Date, time	Magn.	Observations
Hector Mine EQ, California, USA	34.60N, 116.27W Depth 6 km	October 16, 1999, 9:46 UTC	M_w 7.1	Growth in 6-5 days before the seismic shock, no increased variability for the periods of magnetic storms.
Colima EQ, Mexico	18.625N, 104.125W Depth 20 km	January 22, 2003 02:06:34 UTC	M_w 7.6	Enhancement of the variability index in ~10 days before the seismic shock. Insignificance of the response of variability during periods of increased geomagnetic activity.
San Simeon EQ, California, USA	35.706N, 121.102W Depth 7.6 km	December 22, 2003 19:15:56 UTC	M_w 6.5	Pronounced increase in 5 days before the seismic shock, relative growth after magnetic disturbance.
Parkfield EQ, California, USA	35.815N, 120.374W Depth 7.9 km	September 28, 2004 17:15:24 UTC	M_w 6.0	Starts to increasing in ~10 days before the seismic shock. The absolute monthly maximum is observed during geomagnetically quiet period in 6 days before the seismic shock. Increased response to the SSC (Storm Sudden Commencement) and no variability during the main phase of the small magnetic storm (D_{ST} <50 nT).

In the simplest case two measurement points are used: one ("sensor station") is located inside the earthquake preparation area, and the other one ("control station") is located outside it. According to the earthquake preparation area conception the character of the ionospheric variability is different within the earthquake preparation area in comparison with the variability outside it. In general case, it is not obligatory to put the "control" station outside the earthquake preparation area, it is sufficient if it will be quite far from the epicenter. It is supposed that the amplitude of precursor diminishes with the distance from the epicenter. The daily correlation coefficient is calculated for these two stations in the form:

$$C = \frac{\sum_{i=1,k}(TEC_{1,i} - <TEC_1>)(TEC_{2,i} - <TEC_2>)}{k(\sigma_1 \sigma_2)} \tag{2}$$

Here indices 1 and 2 correspond to the first and second GPS stations, TEC (total electron content) is represented by time series, the TEC values are calculated from the GPS measurements, k=96 (or 144) points is the number of samples per day (traditionally k=96 or T=15 min. sampling interval is used for ionospheric sounding, and k=144 or 10 min. interval we normally use for vertical TEC calculations, respectively), the mean value $< TEC >$ and standard deviation s are determined by the expressions:

$$\begin{aligned} <TEC> &= (\textstyle\sum_{i=1,k} TEC_i/k), \\ \sigma^2 &= (\textstyle\sum_{i=1,k}(TEC_1 - <TEC>))/k \end{aligned} \tag{3}$$

The drop of correlation coefficient few days before the seismic shock was observed [13]. One can see the example in Fig. 1a for the case of San Simeon earthquake (M6.5) 22 December 2003 in California.

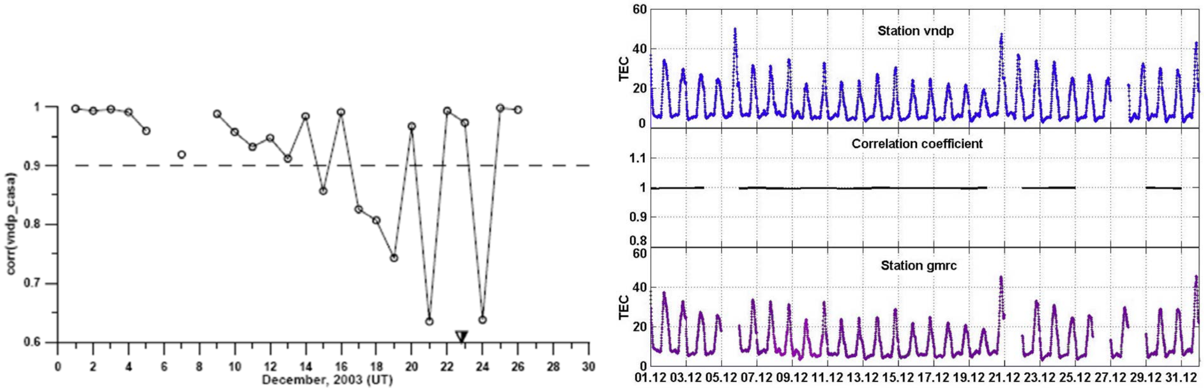

Figure 1: left – Daily cross-correlation coefficient between VNDP and JPLM GPS stations for vertical TEC derived from GPS receivers network at California, USA for December 2003. The time of the San Simeon earthquake is indicated in figures by sign ∇; right – Correlation coefficient (middle panel) for December 2003 between the stations VNDP (top panel) and GMRC (bottom panel).

But under certain circumstances this technique does not work, and the problem (as it was clarified in additional study) is in the complex character of the electron density distribution over the earthquake preparation zone.

We demonstrate here the origin of the possible correlation technique fail. For December of 2003 when the San Simeon earthquake took place we calculated cross correlation coefficients for the different pairs of GPS receivers within the earthquake preparation zone. Calculations for the pair of stations VNDP-GMRC which are quite fare one from another demonstrated that the correlation coefficient is close to 1 (Fig. 1b) for the whole December 2003. The problem is in the complex distribution of the electron concentration over the earthquake preparation area discussed in [15]. It can happen that the station close to the epicenter may not "feel" the seismo-ionospheric variations. One can see that the stations to the North-East and to the South-East directions (Fig. 2a) will "see" the effect while the stations VNDP and GMRC situated on the same level of TEC will not be effective in the precursory variations identification.

3 Regional variability index

The 2D GPS TEC distribution in the form of map may be not very reliable because of the possible constant bias of some stations in relation to another, what can introduce the errors in absolute GPS TEC maps. We found the simple way to describe the variability within the area of analysis. The special index of variability which is the difference between the maximal and minimum values of TEC for every given moment for all the stations under analysis was calculated for the periods around the time of four important earthquakes (and also taking in account the geomagnetic conditions referring to Dst). Actually, the index presents the data spread on the close situated receivers.

In the case of San Simeon earthquake, taken as example (Fig. 2b), one can observe the increase of variability 5 days before the seismic shock. Also some variability increase is observed after magnetic disturbances, for example, from 5th of December. Nevertheless, this variability is much lower than during pre-earthquake period. Similar observations for another 3 earthquakes are summarized in the Table 1.

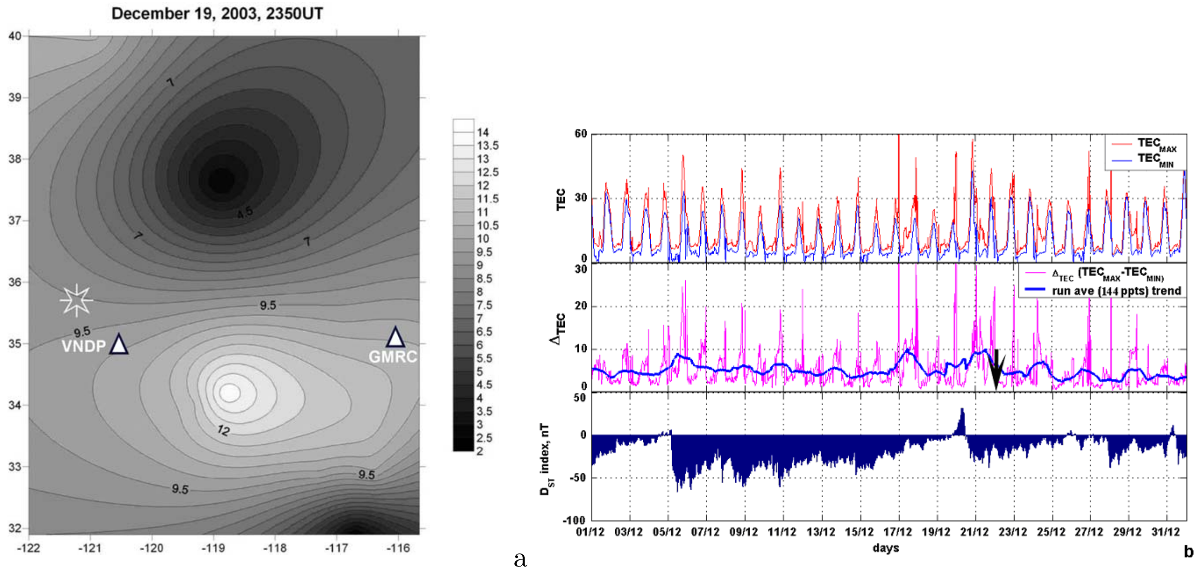

Figure 2: a: TEC distribution over the area of earthquake preparation 3 days before San Simeon earthquake. b: Upper panel – maximum (red) and minimum (blue) values of TEC, middle panel – regional variability index (magenta), running average of the regional variability index (blue) for December, 2003, arrow shows the moment of the San Simeon earthquake, bottom panel – Dst index for December, 2003.

4 Discusion and conclusions

In the all four cases presented in the paper one can observe the increase of regional variability of the ionosphere (in vertical TEC) starting 14–5 days before the seismic shock. The index demonstrates the spread of the TEC over the area few hundred kilometers in diameter. Usually, the receivers register very similar data (with the spread not exceeding few TEC units). In the considered cases the spread reached the value up to 40 TEC units. The smaller value of the variability for the Parkfield earthquake may be explained by the smallest (within the considered set of data) magnitude of earthquake. One should keep in mind that magnitude reflects the exponential change of the energy released during the earthquake.

If we look at the problem from the position of the physical mechanism [8], the variability intensity will depend on the extend of the atmosphere electricity changes (conductivity and vertical electric field). The modification of these parameters is provided by the air ionization produced by radon released from the active tectonic fault before the earthquake. Unfortunately, the USGS stopped the radon monitoring at California, and we can only speculate that the difference (and the time of appearance) of the ionosphere variability is result of dynamics and intensity of the radon release before the earthquakes.

Three different techniques for determination of the ionosphere variability over the area of the earthquake preparation: cross-correlation analysis, regional mapping, and regional variability index. The first two may fail due to the complex spatial distribution of the electron concentration over the area of the earthquake preparation. The proposed variability index shows the increased variability (spread) of the vertical TEC over the area of the earthquake preparation up to 40 TEC units. The probable reasons of the difference of the observed variability intensity are the earthquake magnitude and the amount of radon released from the Earth's crust before the earthquake.

This work will be continued to collect more statistics, and also for other seismically active areas of our planet, including the regions where the real radon monitoring is conducted.

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