

Study of the Ionosphere Irregularities Caused by Space Weather Activity on the Base of GNSS Measurements

Iu. Cherniak¹, I. Zakharenkova^{1,2}, A. Krankowski¹

¹Space Radio Research Center, , University of Warmia and Mazury,

Oczapowskiego, 2, Olsztyn, 10-719, Poland

²Institute De Physique Du Globe De Paris

Paris, France

ABSTRACT

The study of ionospheric density gradients and irregularities distribution is not essential in fundamental ionosphere-magnetosphere coupling investigations in terms of plasma conductivity that play a major role as well as very important for practical aspects related with trans-ionospheric radio wave propagation conditions. The ionosphere delay is the biggest error source for satellite navigation systems. The GNSS signal fading due to electron density gradients and irregularities in the ionosphere raise a concern about the operational availability of navigation systems. The intensity of such irregularities on high and mid latitudes essentially rises during space weather events. Existing permanent GNSS networks provides opportunities to estimate the overall levels of ionospheric density gradients and irregularities as well as to study them spatial and temporal evolutions.

The our methodology based on rate of GPS TEC estimates, ROTI index and mapping techniques allows to estimate day to day irregularities patterns in geomagnetic coordinates. By processing of data from more than 700 permanent GNSS station (in the Northern Hemisphere) per day it was obtained that the occurrence and magnitude of TEC fluctuations, measured using GNSS networks, increase dramatically during space weather events. To illustrate these effects it was presented results of observations and analysis for specific periods of new solar cycle. Our results demonstrate that the occurrence and magnitude of TEC fluctuations, measured using GNSS networks, increase dramatically during space weather events. The irregularities oval expands equator-ward with simultaneous increase of the fluctuation intensity. The study, modelling and prediction of the ionospheric irregularities at midlatitudes and subauroral regions is actual from practical view task because a lot of GNSS users are situated in this area. The statistical analysis of data from the permanent GNSS network together with space weather indices allows to develop approaches for the empirical modeling of the ionospheric irregularities for the Northern Hemisphere. With ROTI index maps it was determined the irregularities oval border and averaging parameter – semi-hemisphere fluctuation index. It was investigated the correlation dependences between Kp geomagnetic index and parameters that characterized the ionosphere irregularities for period of 2010 – 2014 years.

1. INTRODUCTION

The physics of the ionosphere irregularities and them effects on GNSS has been studied for several decades. The ionospheric activity in polar, subauroral and midlatitude regions is primarily associated with geomagnetic storms, coronal mass ejections and coronal holes etc. Processes in ionosphere during this events lead to formation of horizontal TEC gradients with the enhancement of TEC which leads to phase as well as amplitude scintillation as reported by many researchers [Jakowski et al, 2004]. If electron density irregularities cover a big area above receiver, there is a high probability

that a receiver can lose more than one satellite signal simultaneously. Therefore, strong ionosphere TEC gradients and resulted fluctuations and signal scintillations could be hazardous in terms of continuity and availability for GNSS navigation (*Forte and Radicella, 2004*).

Ionospheric irregularities can be characterized by measuring its impact on amplitude and phase of the received GNSS signal. The widely considered measures are the scintillation indices (f.e. S4 index, and the TEC rapid changes. When the scintillation events of S4 occur, the probability that the TEC fluctuation simultaneously occur is very high. Based on the results reported by Pi et al. (1997), Basu et al. (1999), Beach and Kintner (1999) there was done conclusion that Rate of TEC index (ROTI) could be used as a proxy for assessing the presence of ionospheric scintillation. So, ROTI can be regarded as an effective indicator of the presence both of phase fluctuations and the amplitude scintillation in the ionosphere. Ionospheric irregularities manifested as a phase fluctuations can be detected using thousands of permanent GNSS stations already deployed around the globe.

2. DATA AND METODOLOGY

In this study we make use of GPS measurements provided by ground-based networks of GPS receivers. Here we considered the polar, subauroral and midlatitude regions of the Northern and Southern hemisphere, that located from 30° geomagnetic latitudes towards the poles. This area is covered by permanent GNSS stations of the IGS, EPN, POLENET-G-NET and several regional networks. Our initial database includes raw observations up to 3500 permanent stations located worldwide and then we deselect equatorial and low-latitude stations. As a result, we have available ~700 stations for the Northern hemisphere (Figure 1a). Such number of stations provides quite enough data for representation a detailed structure of the ionospheric irregularities pattern.

Rate of TEC (ROT), as a measure of phase fluctuation activity, is calculated using the algorithm, that was proposed by *Pi et al. [1997]*. ROT is calculated in units of TECU/min for each visible satellite over GNSS station. The ROT values are calculated and then de-trended for all individual satellite tracks for elevation angles over 20 degrees. As it was already mentioned above, the ROTI can effective characterize the ionospheric fluctuation activity. ROTI is defined as the standard deviation of the detrended rate of change of TEC (ROT) [*Pi et al., 1997*]. Based on the retrieved values of ROT, the ROTI values are calculated over 5-minute periods with running window for each station. To observe the spatial behaviour of the ionospheric fluctuations we process ROTI data from considered multi-site database and visualize result in the form of ROTI map. Here it was used a single-layer model and locations of the TEC fluctuations are related to the locations of the ionosphere piercing points. Due to strong connections between the Earth's magnetic field and the ionosphere, the behaviour of the fluctuation occurrence is represented as a function of the magnetic local time (MLT) and of the corrected magnetic latitude. Each map, as a daily map, demonstrates ROTI variation with geomagnetic local time (00-24 MLT). ROTI maps are constructed with the grid of 2 deg x 2 deg. The value in every cell is calculated by averaging of all ROTI values cover by this cell area and it is proportional to the fluctuation event probability in the current sector.

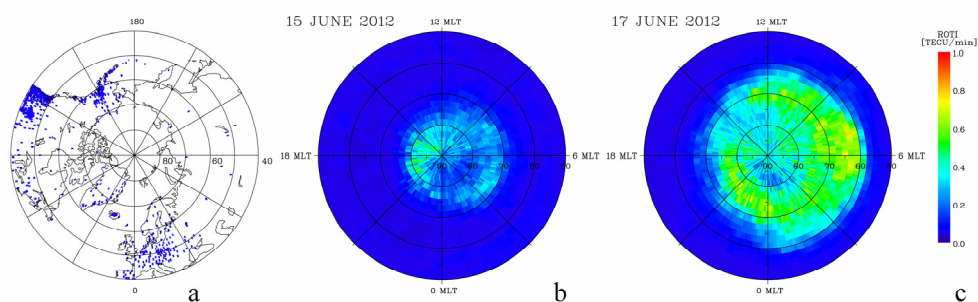


Figure 1. Location of GNSS stations involved into processing (a), the ROTI maps for quite and disturbed geomagnetic conditions.

The ROTI maps, constructed by such way, allow to estimate the overall fluctuation activity and auroral oval evolutions (Figure 1b-c).

3. IONOSPHERIC IRREGULARITIES MEASURED USING GNSS NETWORKS: CASE STUDY

It is known that structure and dynamics of the ionosphere are highly sensitive to the geomagnetic disturbance activity that occurs regularly within the Earth's magnetosphere. Occurrence of ionospheric irregularities is difficult to predict and to model, because of the temporal and spatial variability of the ionosphere and solar activities that are driving forces of space weather phenomena. The constructed ROTI maps allow to estimate the overall fluctuation activity and auroral oval evolutions. To show these possibilities it was investigated the development of ionospheric irregularities during geomagnetic storm of 24 October, 2011. This geomagnetic storm initiated by sharp increasing of proton flux and and pressure with the maximum before the 23:00 UT on 24 October, 2011, sharp changing of magnitude and sign of IMF Bz component (Fig. 4). The Dst index reach minimum value -118 nT at 05:00 UT on 25 October 2011. Additionally, before the main storm phase there was remarkable increasing of the solar wind density and pressure, as well as remarkable variations of IMF Bz component on 23 October, 2011. The duration of the main phase of geomagnetic storm was about 4h and then the recovery phase started with duration about 48 h. As reported by de Jesus et al. [2013], this geomagnetic disturbance with fast decrease of Dst on the night of 24–25 October lead to a prompt penetration of electric field of magnetospheric origin to ionosphere ant to a positive ionospheric storm on the night of 24–25 October observed in the foF2 variations at mid-latitude stations and the GPS-VTEC observations at mid- and low-latitude stations in American sector. During the daytime on 25 October, the variations in foF2 and TEC at mid-latitude stations show large negative ionospheric storm.

Figure 2 presents the variability of ROT values for period of 23-28 October 2011, calculated for all visible GPS satellite passes over chain of selected European GNSS stations, stretched from 70N to 50N practically along the same meridian. It was observed the intensification of fluctuation activity on 23 October after 12 UT at stations in polar region TRO1 and KIRU. This fluctuation related with comparatively moderate increasing of solar wind density and pressure and slow variations of IMF Bz (not presented).

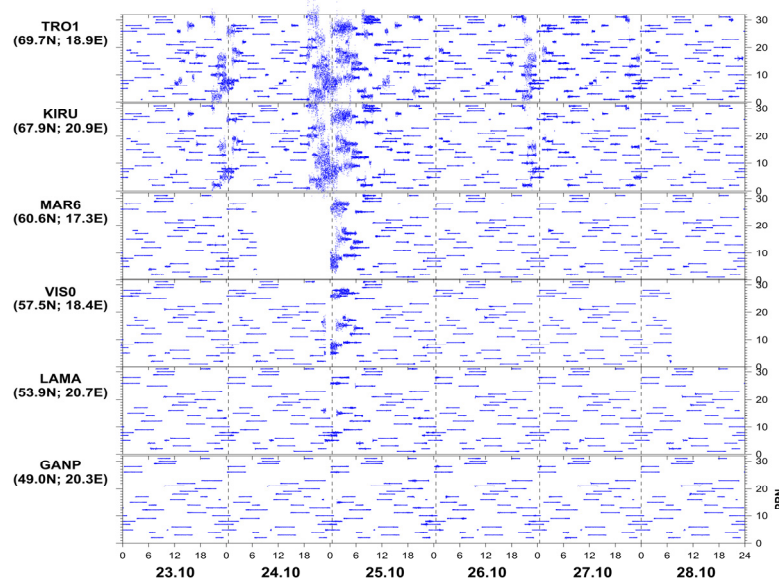


Figure 2. Variability of ROT values over chain of selected GNSS stations (23-28 October 2011).

The most intensive fluctuations observed after 18 UT on 24 October, the beginning of this effect started before IMF Bz component rapid changes and controlled also by solar wind pressure. During period from 22 UT 24 October to 06 UT 25 October the fluctuation activity reached peak and fluctuation events registered even on midlatitude stations VIS0 and LAMA. On geomagnetic storm recovery phase (26-28 October) the strong fluctuation events were registered only on auroral GNSS stations TRO1 and KIRU and during nighttime.

Figure 3 illustrates the structure and intensity of the ionospheric irregularities for the period from 23 to 28 October, 2011. The sequence of graphs shows the day to day evolution of ionospheric fluctuation pattern before the main phase of storm and during main and recovery phase of geomagnetic disturbance. The ROTI maps, constructed by such way, allow to estimate the overall fluctuation activity and auroral oval evolutions.

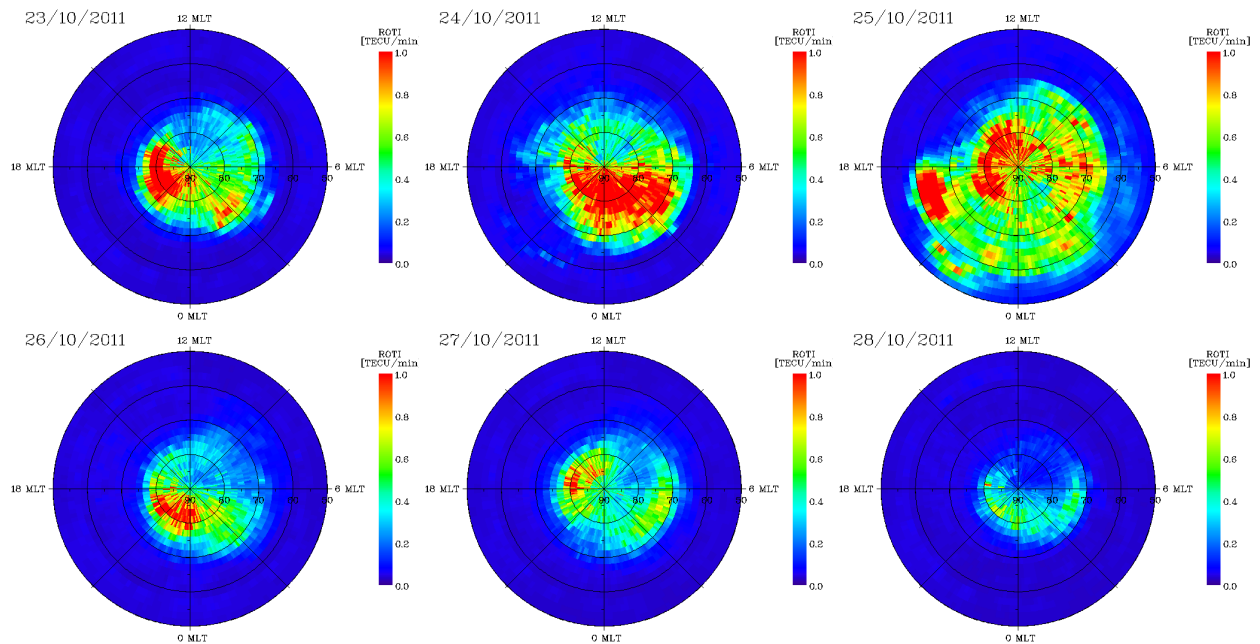


Figure 3. Daily ROTI maps for 23-28 October 2011

The graphs show that at moderate disturbed days before main phase of storm the more intensive irregularities were located in night sector near cusp region and oval border, not crossing 70 degree. With evolution of geomagnetic disturbance the fluctuation activity also raised and expanded to 75° in night sector on 24 October and up to midlatitudes and half of day on 25 October. After magnetosphere and ionosphere recovery and decreasing of solar wind intensity the fluctuation activity pattern registered again near cusp, at night time and with lower intensity in comparison with first considered day of 23 October 2011.

4. THE APPROACHES FOR IONOSPHERE IRREGULARITIES MODELING ON BASE OF ROTI MAPPING

The results of analysis of the ionospheric irregularities manifestation for the presented above case study and for another event for periods 2010-2014 show that the main features of the irregularity pattern are the ROTI index intensity and position of irregularity oval southern border. These parameters strongly depends on the space weather conditions such us solar wind parameters and geomagnetic indices. For estimation of the day-to day fluctuation activity dependences (in form a diurnal ROTI maps) from geomagnetic conditions is more convenient using of Kp index sum for considered day.

As measure of the overall fluctuation activity for selected region is proposed the Hemisphere ROTI index (HROTI, daily values) that taking into account all fluctuation events from mid-latitude to auroral regions. The HROTI index for ionospheric irregularities is calculated by summation of the TEC values multiplied by cell's area. The correlation between HROTI_{ij} with daily sum of Kp (ΣKp) geomagnetic index presented on the fig. 2. It is clear seen strong dependence between fluctuation activity index and Kp. It was relived the strong correlation ($R=0.79$) between ΣKp and HROTI and HROTI values can be modeled using linear predictor function (linear regression model). The linear regression equation with corresponded coefficients presented on the figure 2.

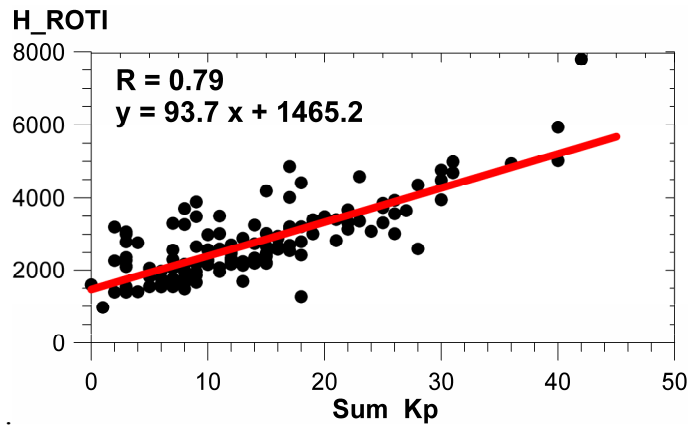


Figure 4. The correlation of the HROTI with sum Kp.

In order to specify the position of irregularity oval southern border it was developed algorithms for determination shape and south border of oval of ionospheric irregularities.

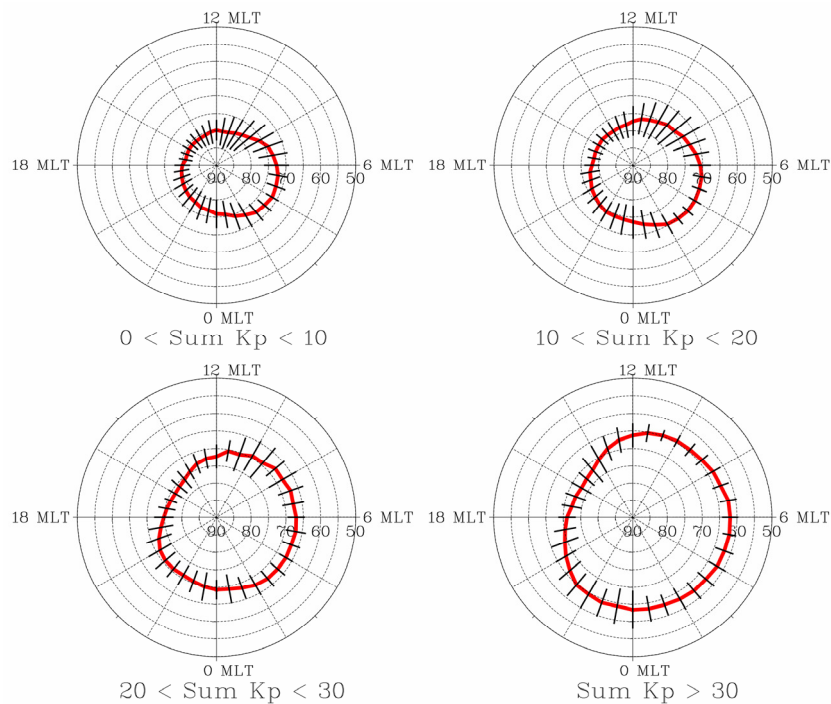


Figure 5. The South border of oval of ionospheric irregularities for different sum Kp index levels.

This algorithms based on the ROTI values analysis of whole ROTI map along selected set of cells from “South” to “North” directions. It was analyzed the dependences of position of the South border of oval of ionospheric irregularities (SBIR) for period 2010-2013. The fig 3 presents the SBIR

positions for different values of the daily sum of Kp geomagnetic index. The SBIR positions (indicated by red line) constructed for sum Kp less than 10; from 10 to 20; from 20 to 30 and more than 30. The solid black lines indicate the standard deviations of calculated values.

The graphs illustrate that at non disturbed conditions equal to sum Kp less than 10 all irregularities were located in night sector and near cusp region and oval border, not crossing 70 degree, oval stretched along line 4 MLT. The averaged HROTI index for such conditions not exceed 2000. When the sum Kp values within 10 to 20 the SBIR expands to 75 degree in night sector. With raising of geomagnetic activity the fluctuation activity also raised (more than 4000 for sum Kp>30) and SBIR expanded to 65° - 60° and can cover sector from 23 to 8 MLT. For geomagnetic conditions when Kp>20 the SBIR can expand on 75° - 70° even in day sector. The resulted statistical dependences, correlation coefficients and regression equations are used as the initial part of ionospheric fluctuation model.

5. CONCLUSIONS

The ROTI maps allow to estimate the overall fluctuation activity and auroral oval evolutions, the values of ROTI index corresponded to probability of GPS signals phase fluctuations as well as the local intensity of ionospheric irregularities (by ROT index) over every processed GNSS stations.

Occurrence of ionospheric irregularities is driven by forces of space weather phenomena and considered case-studies demonstrate the ability to retrieve information about ionospheric irregularities structure, position and duration.

The indices and maps, based on TEC changes, can be effective and very perspective indicator of the presence of phase fluctuations in the high and mid-latitude ionosphere.

The results of our study shows that it is possible to use current network of GNSS permanent stations to revealed the are the ionospheric irregularities intensity described by ROTI index (corresponded ROTI maps and HROTI index) and position of irregularity oval southern border. It was established the correlation dependences and linear regression coefficients between this parameters and geomagnetic index Kp (daily sum Kp).

The obtained results is usable for retrospective estimation of space weather impact on positioning and for the developed now ionospheric irregularities models.

ACKNOWLEDGEMENTS

The authors thank IGS, UNAVCO and EUREF for making available GPS measurements data.

REFERENCES

- Basu, S., K. M. Groves, J. M. Quinn and P. Doherty (1999), A comparison of TEC fluctuation and scintillations at Ascension Island, *J. Atmos. Sol. Terr. Phys*, 61, 1219-1226.
- Beach, T. L. and P. M. Kintner (1999), Simultaneous Global Position System observations of equatorial scintillations and total electron content fluctuations, *J. Geo. Res.*, 104, A10, 22553-22565.
- Forte, B., and S. Radicella (2004), Geometrical control of scintillation indices: what happens for GPS satellites, *Radio Science*, 39. RS5014, doi:10.1029/2002RS002852.
- Jakowski, N., R. Leitinger, and L. Ciraolo (2004), Behavior of large scale structures of the electron content as a key parameter for range errors in GNSS applications, *Annals of Geophysics*, 47, N. 2/3.
- Pi, X., A. J. Mannucci, U. J. Lindqwister and C. M. Ho (1997), Monitoring of global ionospheric irregularities using the worldwide GPS network, *Geophys. Res. Lett.*, 24, 2283.