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INVESTIGATION OF THE INFLUENCE OF STRONG GEOMAGNETIC STORMS ON THE SIGNAL PARAMETERS IN GNSS STATION SOFI

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Key words: *space weather, geomagnetic storm, GNSS, ionosphere, TEC*

Abstract: *The paper presents the first results obtained from analysis of the strong geomagnetic storms' effect upon the GPS signals in IGS/EPN permanent site SOFI, Bulgaria. As an example, a geomagnetic storm in 2004 is considered. For the period 7-12 Nov. 2004 the geomagnetic indexes D_{st} and K_p, variations of the geomagnetic field components in PAG observatory are analyzed simultaneously with the GPS data. The interplanetary medium and interplanetary magnetic filed changes influence on the local variations of the ionosphere parameters above Sofia. It is shown that this strong geomagnetic storm is registered by the geomagnetic indexes D_{st} and K_p, as well with the horizontal H-component of the geomagnetic field and the total electron content (TEC). The established maximum TEC value is 47 TECU or ~4.9 m errors in the measured pseudoranges using two-frequency ground-based GPS receiver on 10 Nov. 2004.*

ИЗСЛЕДВАНЕ НА ВЛИЯНИЕТО НА СИЛНИ ГЕОМАГНИТНИ БУРИ ВЪРХУ ПАРАМЕТРИТЕ НА СИГНАЛА В GNSS СТАНЦИЯ SOFI

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Ключови думи: *космическо време, геомагнитна буря, GNSS, йоносфера, TEC*

Резюме: *В статията са представени първи резултати от анализа на влиянието на силни геомагнитни бури върху GPS наблюденията от IGS/EPN станция SOFI. Разгледан е пример за геомагнитна буря през 2004 г. За периода 7-12 ноември 2004 г. са анализирани съвместно геомагнитните индекси D_{st} и K_p, вариациите на компонентите на геомагнитното поле, регистрирани в геомагнитна обсерватория Панагюрище и данните от GPS измерванията. Измененията на междупланетната среда и магнитното поле влияят върху локалните вариации на йоносферата над София, което е установено чрез D_{st} и K_p индексите, хоризонталната компонента на геомагнитното поле H и тоталната електронна концентрация (TEC) по време на силната геомагнитна буря. За изследваната буря е установен максимум на TEC през 10.11.2004 г. със стойност 47 TECU, което съответства на грешка в определяне на псевдоразстоянията от порядъка на ~4.9 m.*

1. Introduction

The development of Global Navigation Satellite Systems (GNSS*) leads to expanding the scientific researches and applications in different fields of human life and practice. Through the last years, data from permanent GNSS sites are successfully used for the ionosphere studies (Schaer, 1999; Hernández-Pajares et. al., 2011). The obtained results contribute to elucidation of causal links between different geophysical processes and phenomena like effects of solar activity on the high atmosphere of the Earth. The studying of ionospheric physics and dynamics is directly related to such scientific fields as space weather, influence of the seismic activity upon the ionosphere, radio waves propagation in/outside of the Earth's space, and etc.

* Global Navigation Satellite System (GNSS) - a general name for the satellite navigation systems GPS, GLONASS, GALILEO, Compass, GAGAN и QZSS

The ionospheric conditions can significantly change with space and time. They depend on 11-year cycle of the solar activity, geographical location (polar, auroral, mid-latitudes, and equatorial regions), as well as of the season and the time during the day. The ionosphere is a layer of the Earth's upper atmosphere, which is at an altitude of 50 to 600 km above the earth's surface. Comparing to the distance between satellite and receiver of about 20200 km the ionosphere is a thin layer from the earth atmosphere with ~550 km in thickness. It is well known that the solar ultraviolet radiation plays a key role in the ionosphere ionization.

The decreasing of accuracy in GNSS positioning and navigation is mainly due to the slower group velocities of electromagnetic (EM) waves passing through the ionosphere. An interruption of GNSS signal and signal amplitude changes over time can happen due to the ionospheric irregularities, which are constantly changed in space and time. From the various sources of error in the GNSS positioning and navigation, the error due to the delay of the signal passing through the ionosphere is one of the largest and most variable, particularly when using single-frequency receivers (Parkinson & Spilker, 1996). Single-frequency receivers (most consumer-grade receivers are single frequency) require an external input for making the correction of the ionospheric delay.

An additional complication is the fact that the GNSS radio signal moves laterally (sideward) in the ionosphere. The main delay of radio signal is due to the total content of electrons (Total Electron Content - TEC) of the ionosphere. The signal delay is roughly proportional to the TEC present in a column lying along the ray path from the satellite to the receiver located in the ground station. The volume concentration of electrons depends on the geomagnetic latitude of which the receiver is located, time of the day, and satellite's height above the horizon. Significantly greater delays occur for signals from the satellites located close to the horizon, as the signals pass through the greater part of the ionosphere. The determination of TEC in the ionosphere using GPS is widely used method for examining the variations in the ionosphere during quiet space weather (Baran et al., 2003; Ya'acob et al., 2010) and in cases of strong geomagnetic storms (Ho et al., 1998; Afraimovich et al., 2002; Jakowski et al., 2002; Bisi et al., 2008; Rao et al., 2011). The TEC profiles and maps from GPS data are compared with the global ionospheric model like IRI (e. g. Arikan et al., 2007). Especially in disturbed space weather conditions, the forecasting of the TEC-values is critical for communication, radar and navigation systems employing EM waves to cope with the effects of the unpredictable variability of ionospheric parameters.

In this article the problems of the effects of strong geomagnetic storms on GPS measurements and basic equations for the distribution of electromagnetic waves in the ionosphere plasma are briefly outlined. A comparative analysis of the planetary geomagnetic indices and the ionospheric parameters with the estimated time delays of the EM signals and TEC is performed. Initial investigations on the effects of strong geomagnetic storm on GPS measurements in the IGS/EPN permanent station SOFI are conducted. As an example, the case of geomagnetic storm development spanning the period from 7 to 12 Nov. 2004 is considered and the variations of the main ionospheric parameter TEC are represented.

2. Influence of the strong geomagnetic storms on the GNSS measurements

The EM wave moves with less group velocity u_G across the Earth ionosphere than outside it and gets respectively a time delay that depends of the ionospheric plasma conditions. The time delay can be represent by the dispersion relation for EM wave propagation:

(1) $$\omega^2 = \omega_p^2 + c^2 k^2,$$

here ω is the angular frequency, ω_p is the plasma frequency, k is the wave vector and c is the velocity of light in vacuum. In the presence of an external magnetic field, i.e. $B \neq 0$, two extreme cases are considered.

i. The EM wave moves perpendicular to the geomagnetic field.

The dispersion equation in this case is just like the equation (1) and the group velocity u_G of the EM waves depends of the volumetric electron concentration N by $\omega_p = \left(Ne^2 / \varepsilon_0 m\right)^{\frac{1}{2}}$, i.e.

(2) $$u_G = F(N).$$

ii. The EM wave moves parallel to the geomagnetic field.

In this case two dispersion equations are distinguished for two waves with different polarization.

(3) $$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1-(\omega_c/\omega)}$$ R - wave

(4) $$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1+(\omega_c/\omega)}$$ L - wave.

These two waves are circular polarized with left L and right R - polarization. In equations (3) and (4) $\omega_c = \frac{|e|B}{m}$ is the cyclotron frequency of the electron rotation with Larmor's radius, caused by the magnetic field with magnitude *B*. In the case (ii.) the group velocity u_G of EM wave is a function of the volumetric electron concentration *N* and also depends on the magnitude of magnetic field *B*

(5) $$u_G = F(N,B).$$

The geomagnetic field variations caused by one geomagnetic storm are not significant in comparison with the magnitude of the main geomagnetic field. During the geomagnetic storm the time-variable part of the geomagnetic field reaches few hundred nT and the main part for the geographic latitudes of the Bulgarian territory is of the order of 50 000 nT. Based on the above mentioned considerations we can conclude that the electrons concentration and the permanent part of geomagnetic field are significant for the group EM wave velocity in the ionosphere plasma.

3. Mapping of total electron content (TEC) in the ionosphere

The group delay of EM signals passing through the ionosphere is frequency-dependent because the ionosphere is a dispersive medium. For GNSS systems, this feature is being used to create an "ionosphere-free" solution using signals at two different frequencies (Parkinson & Spilker, 1996).

The value of group delay or phase advance velocity of the GPS signal is determined by the total volumetric concentration of electrons along the ray path from the satellite to the receiver. It can be expressed as follow (Kintner, 2008):

(6) $$\delta t = \frac{e^2}{2c\varepsilon m_e f^2 (2\pi)^2} \int_\rho N d\rho ,$$

where *c* is the velocity of light in vacuum, ε is the permittivity of vacuum, m_e is the electron mass and *f* is the frequency of EM wave. In this expression the only variable is the electron concentration *N* in the ionosphere. After some mathematical transformations, this expression yields the form:

(7) $$\delta t = \frac{40.3}{cf^2}.TEC ,$$

where $TEC = \int_\rho N d\rho$ is the so-called slant total electron content, which is marked by TEC_s. TEC is defined by the volumetric concentration of electrons integrated along the ray path ρ of EM signal from each GNSS satellite to the receiver.

Since the concentration of electrons is much larger in the ionosphere than in any other part of the atmosphere, the ionosphere layer has the biggest share in the calculation of TEC (Klobuchar, 1996; Mannucci et al., 1998). TEC is measured in units of 10^{16} electrons/m² = 1 TEC unit (TECU). One TECU produces about 0.35 nsec differential delay (L1 - L2) or error of about 0.105 m in the pseudorange between the satellite and the receiver. The nominal range of TEC is 10 to ~10^2 TECU with minima at midnight and maxima around the afternoon. During a solar cycle maximum, the TEC_v may reach values above 200 TECU. TEC decreases slowly by night due to the recombination of electrons and ions in the ionosphere. The maximum value of TEC usually occurs in the early afternoon and the minimum is usually before sunrise. Daily fluctuations of TEC increase from north to south, as the sunlight is more direct to the equatorial regions (Ho et al, 1998; Jakowski et al., 2002). For TEC-mapping a single-layer (or thin-shell) model in which the entire charge of the electrons is concentrated in the thin shell above the earth's surface in the ionospheric F-field is most commonly accepted. In calm conditions the mean TEC-values are about 15 TECU per day.

GPS signals pass through the ionosphere, which is a shell with different concentration of the electrically charged particles. To compare the total electron content on the ray path of signals at different angles above the horizon at given GNSS station, the slant TEC must be transformed into an equivalent vertical electron content, which is marked by TEC_v. For small angles above the horizon TEC_s can reach up to 3 times the value of TEC in the zenith. The TEC_s is divided by the cosine of the angle above the horizon at an average height of the ionosphere (Klobuchar, 1996), namely:

(8) $$TEC_v = TEC_s \cos z',$$

where z' is the zenith angle at the Ionospheric Pierce Point (IPP) (Fig. 1). Most often the value of the ionosphere height for calculations is assumed that corresponding to the maximum electron concentration in the F2-layer. This height varies from 250 to 350 km for middle latitudes and from 350 to 500 km in the equatorial latitudes, as most often it is taken to be 350 km. Permanent GNSS stations, which are located

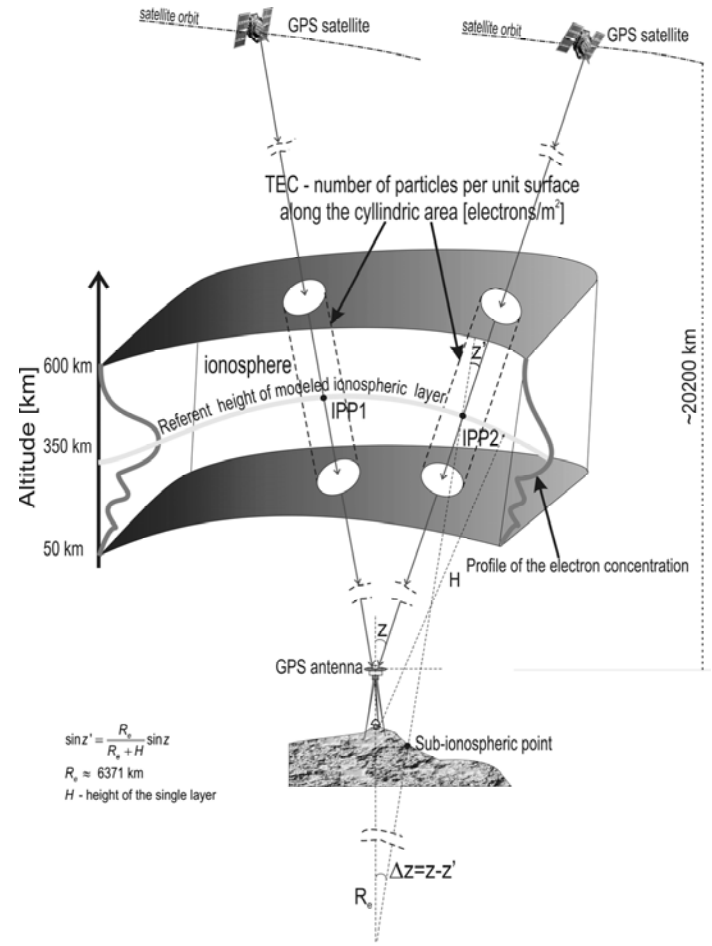

Fig. 1. TEC determination using GPS/GNSS data

on a relatively short distances of each other, make it possible to perform a more detailed TEC-mapping due to the ionospheric irregularities.

In quiet ionospheric conditions, the time delay of the measured pseudorange on L1-frequency can reach from one to several meters. But, under the active ionosphere conditions, such as daytime during the peak of the 11-year solar cycle that governs ionosphere activity, ionospheric delays can reach 50 meters or more (Parkinson & Spilker, 1996). The determination of precise relationships between different parameters included in the models of TEC-mapping with more precise temporal and spatial resolution is still the subject of numerous studies (Arikan et al., 2007; Jakowski et al., 2002; Ya'acob et al, 2010; Rao et al., 2011; Hernández-Pajares et. al., 2011).

4. Permanent IGS/EPN site SOFI

The permanent station SOFI (42.556^{0}N, 23.395^{0}E) as one of the monitoring stations of the International IGS Service and the European Permanent Network (EPN) (http://www.epncb.oma.be) was built in 1997 near the "Ovnarnika" locality (Milev et al., 1998). It is located in the Observatory of the Military geographic service. The GNSS antenna is mounted on a concrete pillar on the building roof and has a height of 6.90 m above the earth's surface. The equipment (antenna and receiver) is replaced several times since 19.05.1997 (the date of the beginning of its work). In the early years the signals only from the satellite navigation system GPS were registered, and since 2005 satellite signals from the Russian navigation system GLONASS are also recorded. Additionally, measurements of some meteorological parameters are performed in order to take into account their influence by applying appropriate corrections to the GNSS observations during the post processing.

The International IGS Service developed the global ionospheric gridded data representing on the TEC-maps, which are computed using data from about 400 permanent GNSS stations world-wide. The IGS/EPN station SOFI is one of the few stations, located on the Balkan Peninsula, which is included in the international analysis centers for GNSS data processing for the space weather research. Analysis centres deliver their results of TEC_v in the IONosphere Exchange (IONEX) format and receiver Differential Code Bias (DCB_s) (Schaer, 1999). The IONEX format allows storing the TEC_v and its estimates in a grid format, and their usage for different investigations.

5. Solar phenomena, planetary geomagnetic indexes and the storm development from Nov. 2004 on the territory of Bulgaria

The strong geomagnetic storm, registered in the period 7-12 Nov. 2004 is proceeded of five solar Coronal Mass Ejections (CMEs) on 4, 6 and 7 Nov. The starting time of these five chromosphere's events according to data of the satellite LASCO C2 are shown in Table 1 (Bisi et al. 2008). These events are the possible causes of the strong geomagnetic storm during the next few days. In the same table, the start time of the interplanetary medium and interplanetary magnetic field disturbances at the Earth orbit registered by satellite ACE are shown too. As a result of the chromospheric events two minimums of the planetary geomagnetic index D_{st} are registered on the Earth surface, which describe the storm on 8 Nov. in 07:00 UT and on 10 Nov. in 10 UT. The geomagnetic index for the studied period is shown on Fig.2.

On 8, 9 and 10 Nov. 2004 the planetary K_p index reaches values more than 8 (Fig.3). On the territory of Bulgaria the geomagnetic storm is expressed by strong decreases of the horizontal magnetic field component *H* which reaches values to -250 nT. The record of H-component variation, registered in the geomagnetic observatory (GO) Panagyurishte (PAG) (42.485°N, 24.177°E) is presented on Fig.4.

The ionospheric conditions on the Bulgarian territory during this storm are registered by the ionospheric station in Sofia (SQ143) (42.70^0 N, 23.40^0 E). The values of critical frequencies f_oE and f_oF2 on 10 Nov. 2004 are shown on Fig. 5. During this day the frequencies reach maximal values for the whole geomagnetic storm period - from 7 to 12 Nov. 2004. As is clearly visible from Fig. 5 the values of f_oF2-critical frequency for the F2-layer are of the order 5 - 7 MHz during the period from 08:00 to 19:00 LT (06:00-17:00 UT).

Table1. Coronal mass ejections, which precede the storm during 7-12 Nov. 2004 according to data from SOHO|LASCO C2, interplanetary disturbances on the data from ACE satellite and the minimums of D_{st} index.

Possible LASCO C2 source (CME)	**Interplanetary counterpart first seen at ACE**	**Geomagnetic activity (D_{st} minimum)**
4 Nov. 2004 - 09:54 UT Halo	7 Nov. 2004 - 22:30 UT	8 Nov. 2004 - 07:00 UT
4 Nov. 2004 - 23:30 UT Partial Halo	7 Nov. 2004 - 22:30 UT	8 Nov. 2004 - 07:00 UT
6 Nov. 2004 - 01:32 UT Halo	9 Nov. 2004 - 20:25 UT	10 Nov. 2004 - 10:00 UT
6 Nov. 2004 - 02:06 UT Partial Halo	9 Nov. 2004 - 20:25 UT	10 Nov. 2004 - 10:00 UT
7 Nov. 2004 - 16:54 UT Halo	9 Nov. 2004 - 20:25 UT	10 Nov. 2004 - 10:00 UT

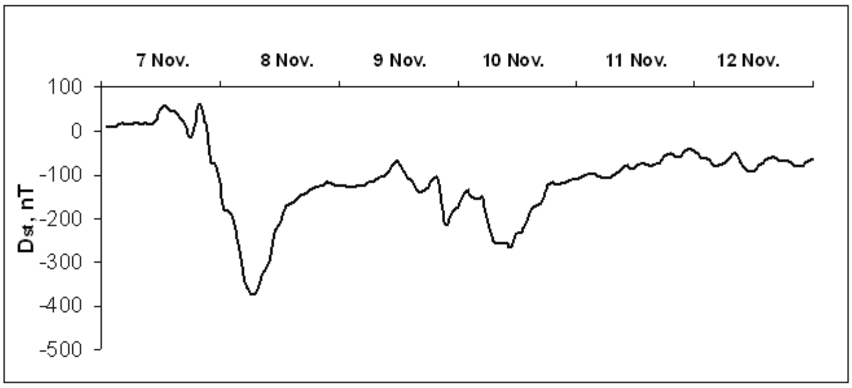

Fig. 2. Planetary geomagnetic index D_{st} for the period 7 -12 Nov. 2004

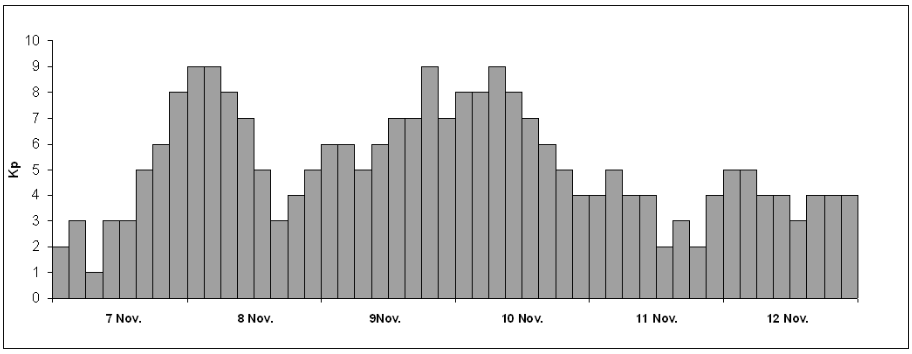

Fig. 3. Planetary geomagnetic index K_p for the period 7 -12 Nov. 2004

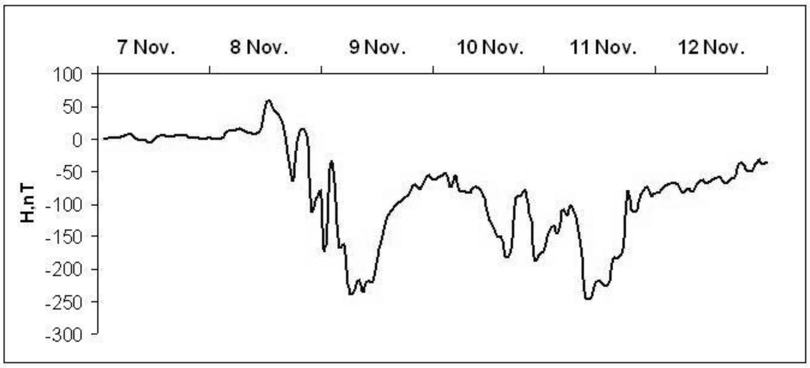

Fig. 4. Variation of magnetic *H*-component in the GO Panagyurishte (PAG)

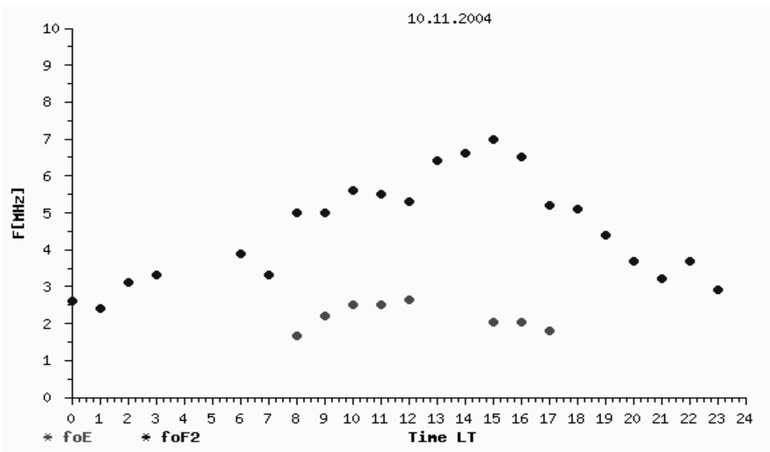

Fig. 5. Critical frequencies obtained from ionospheric station Sofia (SQ143) on 10 Nov. 2004

6. Investigation of the geomagnetic storm influence on GNSS observations in the station SOFI

To investigate the geomagnetic storm influence upon the GPS signals we analyzed as example the measurements from IGS/EPN station SOFI for the period 7 - 12 Nov. 2004, when the geomagnetic storm is observed. The RINEX (Receiver Independent Exchange) files (312-317 DOY), navigation and differential code bias (DCB) files provided by the IGS websites are used to calculate TEC_v.

From the beginning of Nov. 2004 the solar activity is enhanced, causing the geomagnetic storm. The last is the source of the electron contents increasing in the ionosphere over Sofia in comparison with the typical quiet geomagnetic days. During such quiet days the TEC no exceeds 5-10 TECU.

The maximal values of the electron concentration are around noon for every day from the storm period. TEC-values are different for the satellite constellation visible from the IGS/EPN site SOFI. Fig. 6 shows the local sky plots of all visible satellites on 10 Nov. 2004 and during the period 11:00-12:30 UT, their number and PDOP. A graph of the obtained TEC_v calculated for sub-ionospheric pierce points (IPP, see Fig. 1) for the elevation 15^0 above horizon is presented on Fig. 7. On the same figure the maximum values more than 40 TECU are observed for the relatively short period 11:00-12:30 UT. The maximum values of time delay in the ionospheric plasma for the same time interval are also high and reach more than 14 nsec. This leads to more than 4.2 m error for the measured pseudorange using two-frequency GPS receivers. Therefore we can accept that during this period spanning one and half hour, the GPS system was working under the strong geomagnetic storm influence, which causes big errors in the positioning and navigation.

7. Conclusions

A maximum variation of the electron concentration N and TEC on 10 Nov. 2004 during 11:00 to 12:30 UT is established when a biggest delay of the GPS signals is determined comparing to the rest days of the strong geomagnetic storm. During this period the record of GO Panagyurishte (PAG) shows a second strong decrease in the horizontal geomagnetic *H*-component of about -180 nT. Data for the same period of the ionosphere station Sofia (SQ143) show values of critical frequencies, reaching ~7 MHz. There is a sudden change of the ionospheric parameter f_0F2 with amplitude about 1 MHz within the period 11:00 – 12:00 UT (12:00 -13:00 LT). This is probably due to the traveling ionospheric disturbances

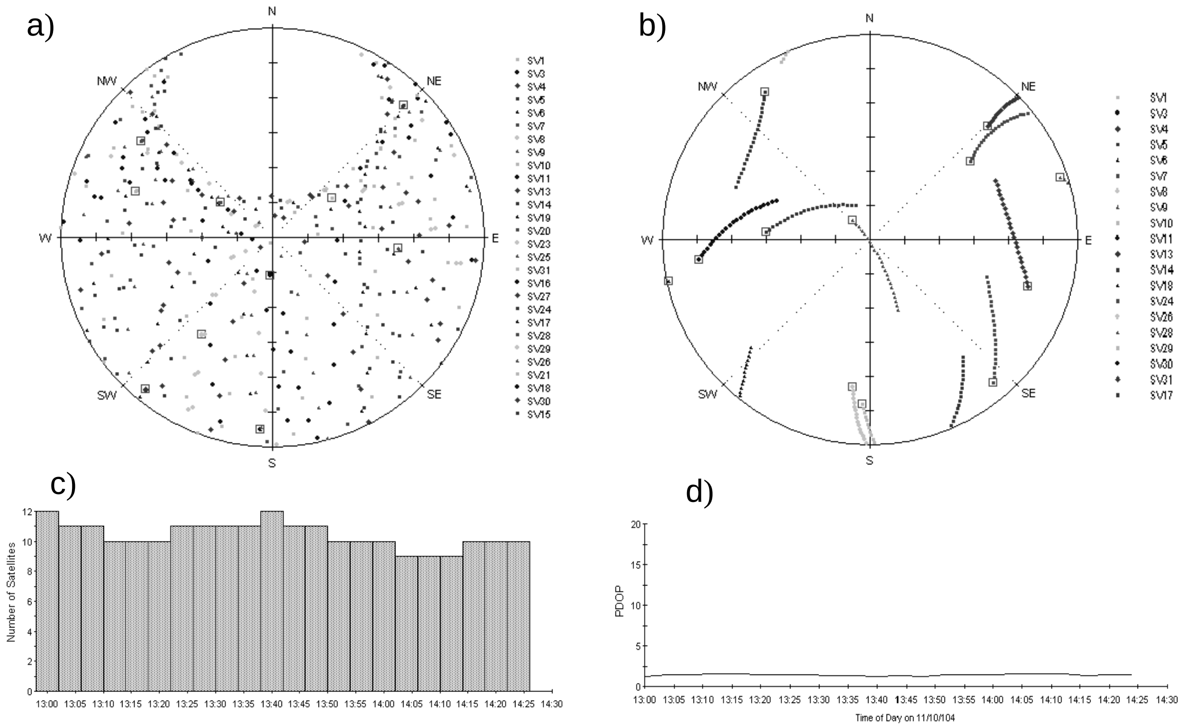

Fig. 6. a) Local sky plots of the satellite constellation visible from IGS/EPN site SOFI on 10 Nov. 2004 (visible satellites are marked with squares); b) local sky plot for the period 11:00-12:30 UT; c) number of visible satellites at one time; d) PDOP

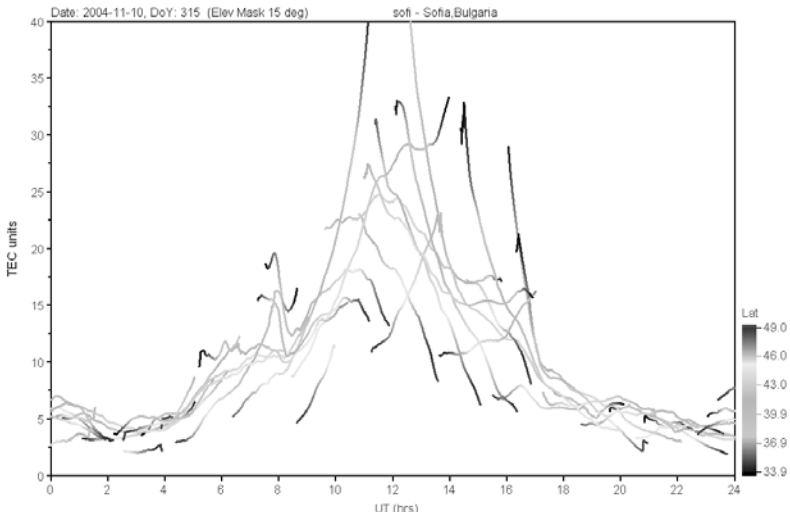

Fig. 7. TEC values determined for observed satellites on 10 Nov. 2004 in IGS/EPN site SOFI

with dynamic jump of the electronic concentration at that time over Sofia. The established maximum TEC-value is 47 TECU based on the GPS observations (~4.9 m error in the measured pseudoranges using two-frequency GPS receiver). This TEC-value can be explained by the influence of the northern edge of the equatorial ionosphere anomaly on EM signals from the visible satellites depicted in bottom side on Fig. 6b.

In this first study a strong local inhomogeneity of the ionosphere and variations in the signal parameters of GPS system are established during the strong geomagnetic storm spanning the period 7-12 Nov. 2004. The results show that during geomagnetic storms large errors in GNSS navigation can be caused. In some cases the connection between ground-based stations and satellites can be interrupted (Hernández-Pajares et. al., 2011). It is necessary to increase the spatial and temporal resolution of the TEC-mapping and forecasting based on the GNSS data from nearby located permanent stations. Denser network from permanent stations allows improving the accuracy in the ionospheic corrections for GNSS navigation using different receiving equipments.

Based on this study we conclude that the mutual analysis of data from permanent GNSS stations, geomagnetic observatories and ionospheric stations contributes to the investigation of ionospheric conditions in low and high geomagnetic activity. As is known, this activity is directly related to the global changes in the space weather. The impact of the interplanetary changes caused by solar activity reflects on the local changes of the ionospheric state above Sofia as shown in this work. Future investigations are needed to improve and guarantee the high accuracy of the radio-based navigation systems used on the Bulgarian territory, by understanding, mapping and predicting the physical phenomena and technological failings which can affect navigation signals.

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