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Research Article / Araştırma Makalesi

THE EFFECTS OF TOTAL ELECTRON CONTENT ON RELATIVE GPS POSITIONING

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ABSTRACT

Total electron content (TEC) is a parameter that represents ionosphere. Global Positioning System (GPS) positioning is affected from the variations of TEC. Strong geomagnetic storms have an effect on both TEC and GPS observations. One of the period for the severe storm on July 14-17, 2000 (Day of year –DOY– 196-199) were chosen to calculate TEC values and North, East and Up coordinate components (n, e, u) for 2^h time intervals. TEC values are calculated at ISTA, TUBI and BUCU stations. In the severe storm period, TEC values are decreased from 16 TECU to 3 TECU against its usual day level at 00-02 Universal time (UT) on DOY 198. In addition, n, e and u coordinate components are obtained for 2^h time intervals from the three baselines. n, e and u coordinate components are higher in the afternoon hours than the other time interval because of the high TEC.
Keywords: Global positioning system, ionosphere, total electron content.

TOPLAM ELEKTRON YOĞUNLUĞUNUN BAĞIL GPS KONUMLAMASINA ETKİLERİ

ÖZET

Toplam elektron yoğunluğu (TEC) iyonosferi temsil eden bir parametredir. TEC'deki değişimler Küresel konumlama sistemi (GPS) ile konumlamayı etkiler. Güçlü manyetik fırtınalar TEC ve GPS gözlemlerini etkiler. 14-17 Temmuz 2000 tarihini içeren günlerde (Yılın günü –DOY– 196-199) şiddetli manyetik fırtına meydana gelmiş ve bu günler 2 saat zaman aralıkları için TEC değerlerini ve Kuzey, Doğu ve Yukarı koordinat bileşenlerini (n, e, u) hesap etmede kullanılmıştır. TEC değerleri ISTA, TUBI ve BUCU istasyonlarında hesaplanmıştır.
198. GPS günü, 00-02 Evrensel saatindeki (UT) Manyetik fırtına esnasında, TEC değerleri normal gün için olan 16 TECU'dan, 3 TECU'ya düşmüştür. Buna ek olarak, 2 saatlik zaman aralıkları için n, e, u koordinat bileşenleri 3 baz için elde edilmiştir. Yüksek TEC değerleri nedeniyle, öğlen saatlerinde bazların bir kısmında diğer zaman aralıklarına göre daha yüksek değerler görülmektedir.
Anahtar Sözcükler: Küresel konumlama sistemi, iyonosfer, toplam elektron yoğunluğu.

1. INTRODUCTION

One of the major error sources on Global Positioning System (GPS) positioning is ionospheric refraction which causes signal propagation delays [1]. Ionospheric refraction depends on the Total Electron Content (TEC) in the signal path which can be modeled by using the GPS observations.

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TEC variations depend on the local time of the day, seasons, solar cycle, geographic location of the receiver and earth's magnetic field [2, 3].

Several researchers showed that TEC values can contribute to understanding of the disturbances of the ionosphere related with geomagnetic storms [4, 5]. Ionospheric disturbances and diurnal variations formed by the TEC in the ionosphere are related to the ionization process. In the mid-latitude region, the ionization process is controlled by X-ray emission and energetic ultraviolet radiation from the sun. The ionization process is chemical reaction that results in neutral atmosphere and ionized particles [6]. Several studies were made in order to show the effect of the geomagnetic storms on TEC values in mid-latitude region. [7] Suggested that the penetration of magnetospheric electric fields into the mid-latitude ionosphere is the mechanism responsible for the mid-latitude ionospheric perturbations resulting that a large (~30%) decrease in the mid-latitude ionospheric plasma density and TEC. A global response to the geomagnetic storm is studied by [8]. [9] Investigated the high latitude ionospheric effects on positioning for increased TEC conditions during the ionospheric storm conditions. In this paper, TEC values around Turkey are studied in the severe geomagnetic storm conditions in order to show the changes of coordinates at the selected baselines.

2. ESTIMATION OF TOTAL ELECTRON CONTENT

TEC is calculated by using geometry-free linear combination (L_4) that is obtained from L_1 and L_2 carrier phase observations. Bernese 5.0 GPS Software is used for the processing of GPS phase observations in order to obtain TEC. The basic GPS zero difference L_1 and L_2 carrier phase observations can be written as,

$$L_{1k}^i = \rho_k^i - I_{1k}^i + T_k^i + c\delta_k - c\delta^i + mp_1 + \lambda_1 n_{1k}^i + \varepsilon_1 \tag{1}$$

and

$$L_{2k}^i = \rho_k^i - \frac{f_1^2}{f_2^2} I_{1k}^i + T_k^i + c\delta_k - c\delta^i + mp_2 + \lambda_2 n_{2k}^i + \varepsilon_2 \tag{2}$$

where ρ_k^i is the geometric distance between the satellite and the receiver, c is the speed of light in a vacuum, δ_k is the receiver clock error, δ^i is the satellite clock error, I_{1k}^i is the ionospheric phase delay, T_k^i is the tropospheric delay, f_1 is the frequency of L_1 signal, f_2 is the frequency of L_2, mp_1 is the multipath effect on L_1, mp_2 is the multipath effect on L_2, n_{1k}^i and n_{2k}^i are the initial carrier phase ambiguities for two frequencies with the corresponding wavelengths λ_1, λ_2, and ε_1, ε_2 are the noise terms for the two frequencies [10]. Using the L_1 and L_2 observations, L_4 ionosphere-free linear combination:

$$L_4 = L_1 - L_2 \tag{3}$$

This basic equation for least square adjustment is as follows:

$$L_4 + v_4 = -\alpha \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) F_I(z)\ E_v(\beta,s) + B_4\ ; \qquad F_I(z) = 1/\cos z' \tag{4}$$

In this equation; α= 4.03 10^{17} m s^{-2} $TECU^{-1}$, v_4 is the residual of L_4, $F_I(z)$ is the mapping function, $E_v(\beta, s)$ is the vertical TEC as a function of geographic latitude, (β) and sun-fixed longitude, (s) of ionospheric pierce point, $B_4 = n_1\lambda_1 - n_2\lambda_2$ is the ionospheric bias, z'

is the zenith distances at the height of the single layer, the remaining notation was as explained above [10, 11]. $E_v(\beta, s)$ is modeled as a truncated Taylor series with β and *s* that can be written as,

$$E_v(\beta, s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{m_{max}} E_{nm} (\beta - \beta_0)^n (s - s_0)^m \quad (5)$$

where, n_{max} and m_{max} are the maximum degrees of the two-dimensional Taylor series expansion, E_{nm} is the TEC coefficients of the Taylor series, (β_0, s_0) is the geographical coordinates of the origin of the development, s_0 is the hour angle of the corresponding to the middle of the observation interval, β_0 is the mean value of the latitudes of all stations used to compute the model. The unknown parameters E_{ik} and at least one B_4 parameter for each satellite and receiver are estimated in a least square adjustment [10, 11, 12]. In this study, zero-degree coefficients E_{oo} are extracted from the ionosphere model that is calculated by the Bernese 5.0 GPS software for site-specific estimation of TEC.

2.1. Processing strategies

24 hours RINEX data with a 30 seconds sampling rate and 15^o elevation mask were used. The height of the ionospheric layer is selected as 400 km with the $F_I(z)$ mapping function in a sun-fixed reference frame. 24^h RINEX files were divided into 2^h non-overlapping time periods. Zero-degree coefficients E_{oo} (TEC) are obtained from the ionospheric models using 2^h RINEX data. TEC values are given in total electron content unit (TECU) that is equal to 10^{16} el/m^2. A Single Layer Model (SLM) was used in order to model the electron content. The SLM is based on the assumption that all free electrons are concentrated in a layer of infinitesimal thickness at a height *H* above the earth surface [11].

3. OVERVIEW OF TEC BEHAVIOUR IN THE MID-LATITUDE REGION

In this study, three permanent GPS stations were used in order to obtain the TEC.

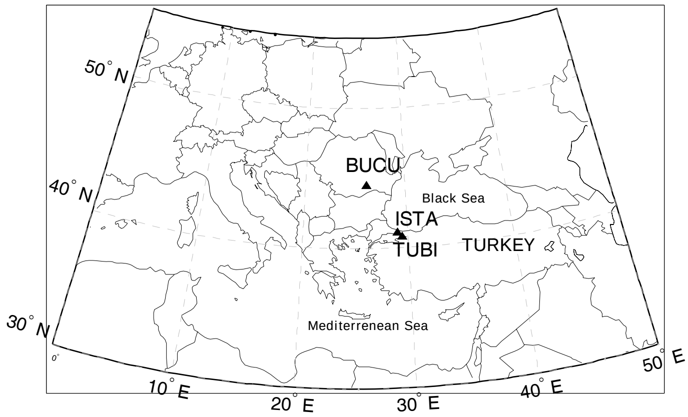

Figure 1. Locations of permanent GPS stations

The stations in the mid-latitude region are ISTA (+41° 06'N, +029° 01'E), TUBI (+40° 47'N, +029° 27'E) and BUCU (+44° 27'N +026° 07'E), respectively. Figure 1 shows the distribution of these stations in Istanbul, Turkey (ISTA), Gebze, Turkey (TUBI) and Bucuresti, Romania (BUCU). RINEX observation files are obtained from the SOPAC web site [13]. ISTA and BUCU stations are equipped with Astech ZXII3 and TUBI is equipped with Trimble 4000SSI receivers. TEC values of the stations are calculated for DOY 196-199 comprising the time interval that the severe geomagnetic storm occurred.

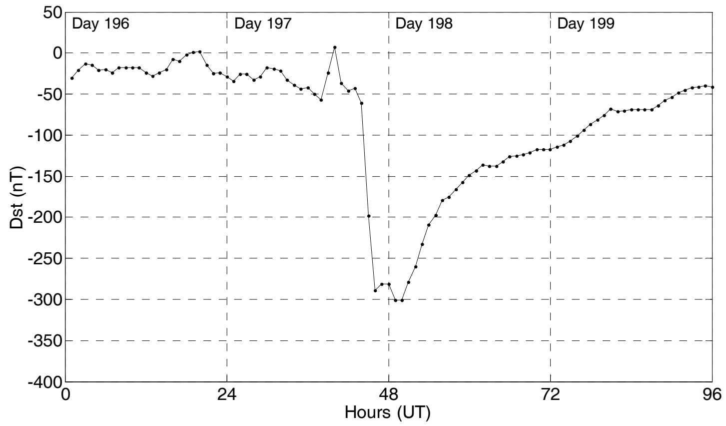

Figure 2. Dst values for disturbed days from DOY 196 to 199, 2000

Diurnal and disturbance-dependent changes on the ionospheric TEC depend on the space weather. Therefore, there is a strong relationship between geomagnetic storms and variations in the ionospheric total electron content [14]. Geomagnetic storms can be monitored by the Dst index. It can be seen from the Figure 2 that the severe geomagnetic storm occurred at 21:00 UT on DOY 197. The Dst index value is -300nT at 21:00 UT.

Figures 3 and 4 show the TEC values for the selected stations. In these Figures, X axes shows hours in Universal Time (UT) and Y axes shows TEC values in TECU. Solid line in the figures depicts TEC values obtained from the Bernese GPS software ionosphere modeling module. Dash-dot lines depict that the TEC values obtained from the Global Ionosphere Model (GIM) in order to compare the results. GIM values are obtained from the Center for Orbit Determination in Europe (CODE) analysis center.

Figure 3a and 3b show 2 hourly TEC values observed at ISTA and TUBI stations from DOY 196 to 199 for disturbed days, respectively. The diurnal TEC values range from 19 to 48 TECU for undisturbed days (DOY 196). TEC changes irregularly for disturbed days compared with the undisturbed days. The minimum TEC value is observed as 4 TECU in the time period that the most severe geomagnetic occurred at 00-02 UT on DOY 198. This expected result indicates that the severe geomagnetic storm affects TEC unfavorably. This can be verified with the Dst index for the same time period given in Figure 2. Furthermore, TEC regular behavior on DOY 196 changes to irregular one on DOY 197 as the Dst index decreased to -300nT level. This irregular behavior was still in progress on DOY 198. The maximum TEC values drop off about 28 from 48 TECU on DOY 198 compared with the other days. Bernese TEC values are also consistent with GIM. There is a strong correlation between Bernese TEC and GIM TEC.

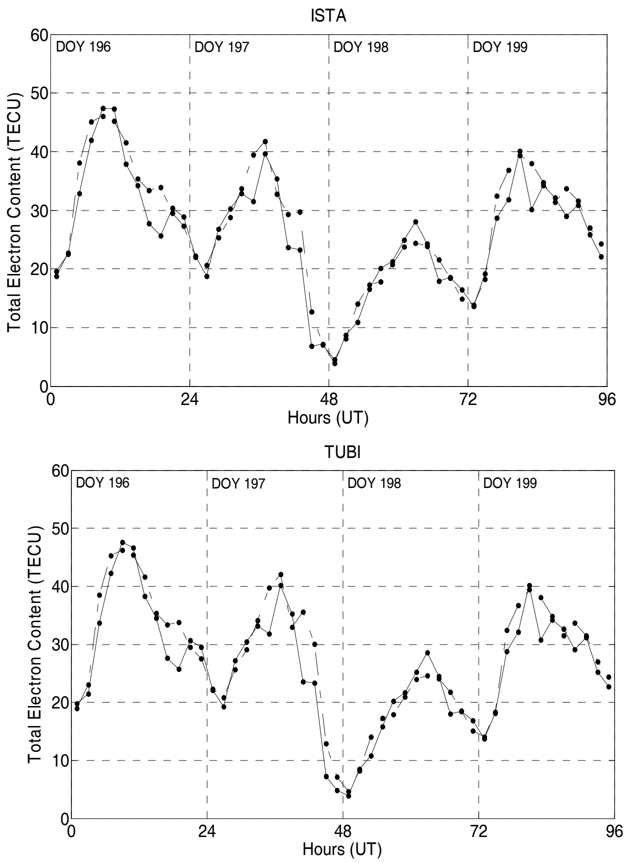

Figure 3. TEC values from DOY 196 to 199, 2000 at **a.** ISTA station and **b.** TUBI station

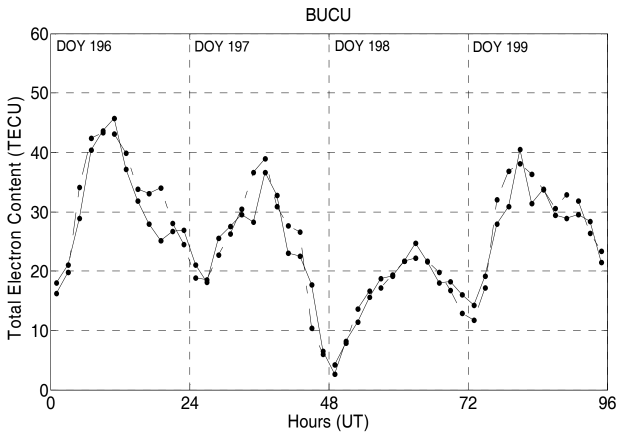

Figure 4. TEC values at BUCU station from DOY 196 to 199, 2000

The diurnal TEC values for BUCU station range from 14 to 48 TECU for undisturbed days (DOY 196) and 3 to 25 TECU for disturbed days (DOY 198). The minimum TEC value is observed as 3 TECU including the time period that the most severe geomagnetic occurred at 00-02 UT on DOY 198. These results show that the BUCU station's TEC behavior is also drastically affected by the severe geomagnetic storm.

4. COORDINATE COMPONENT

Different baselines are obtained in order to show the effects of TEC variations on the north, east and up coordinate components (n, e, u). ISTA station is held fixed in the solutions and baselines are referenced to this station. Then n, e and u coordinate components of the stations are obtained from the 2^h processing solutions. The processing is done with the data obtained from the IGS and MAGNET (MArmara Continuous GPS NETwork) networks using Bernese GPS software v 5.0 (Figure 5). The GPS data is in 30 second sampling rate in RINEX format. Troposphere is modeled with Saastamoinen model which is chosen as default value in control panel in the preprocessing step. Saastamoinen model is a priori model that is corrected by site-specific troposphere parameters. Site-specific troposphere parameters that are estimated in the parameter estimation step give station and time-dependent corrections to the a priori model [10]. Ionospheric effects are reduced with the global ionospheric model obtained from CODE and with the stochastic ionosphere parameters (SIP) for each epoch. Elevation mask is selected 15^o to reduce cycle slips and multipath effects. IGS precise ephemerides are used [15].

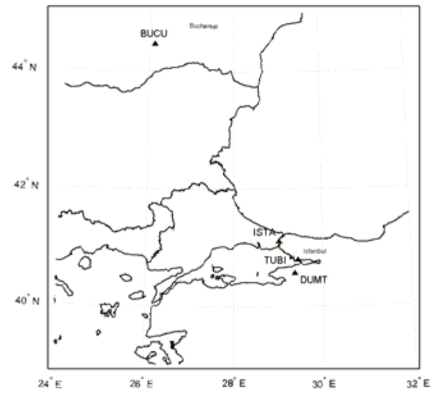

Figure 5. Test network

In the next step of the study, n, e and u coordinate components are analyzed and correlated with the TEC. The extreme values for n, e and u coordinate component are estimated as 20, 40 and -40 mm at ISTA-BUCU baseline; 2, 40 and -19 mm at ISTA-TUBI baseline. n, e and u coordinate components for the mentioned baselines are higher at 10-12 UT on DOY 196 than the remaining time intervals for the same hours. n, e and u are 22, 18 and -40 mm, respectively, at ISTA-DUMT baseline at 08-10 UT on DOY 199. TEC values are high in these time periods as well.

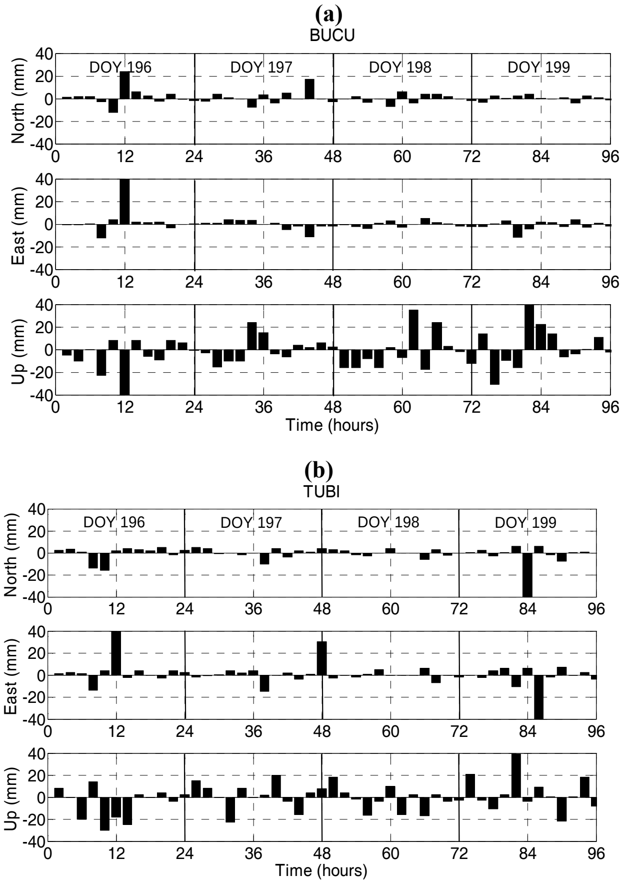

Figure 6. n, e and u coordinate components from DOY 196 to 199, 2000 at **a.** ISTA-BUCU baseline (442 km) **b.** ISTA-TUBI baseline (51 km)

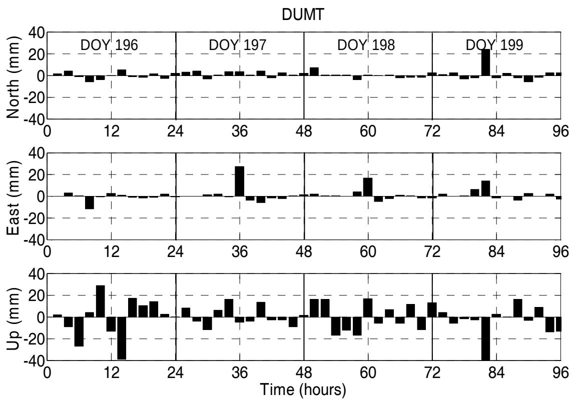

Figure 7. n, e and u coordinate components from DOY 196 to 199, 2000 at ISTA-DUMT baseline (67 km)

Low level values in the n, e and u coordinate components can be seen at all baselines at 21:00 UT on DOY 197 even though the geomagnetic storm begun at this time. n, e components are ±2mm and u components are about ± 5mm. It can be said that there is no significant high amplitude variations in the n, e and u coordinate components at 21:00 UT on DOY 197 when the geomagnetic storm took place. In addition, the low level coordinate components for all baselines can also be seen on DOY 198. n and e coordinate component values are commonly between ± 5mm level, whereas ± 20mm level for u component for all baselines.

The up component's amplitudes are higher compared with the other components that can be explained by its dependence of tropospheric gradients. Therefore, 2 hour processing results show that the changes in the n, e and u coordinate components are independent from the geomagnetic storm for the selected time period and baselines around Turkey. The low level TEC is responsible for the low amplitude variations in the n, e and u coordinate component. n, e and u coordinate component values are at the level of ± 5 mm at 00:00 UT for all days whether geomagnetic storm occurred because the TEC values are about 20 TECU.

5. CONCLUSIONS

In this paper, TEC is analyzed for geomagnetic storm conditions in order to show TEC variations and its effects on positioning in different space weather conditions. Diurnal minimum TEC decreased to 5 TECU level in the storm time period. Ionospheric TEC is unfavorably decreased in the geomagnetic storm in the selected part of the mid-latitude region. In addition, the TEC time series preserve its similar behavior for ISTA, TUBI and BUCU stations even in geomagnetic storm days.

Geomagnetic storm effects can not be seen in the n, e and u coordinate components even though the processing time interval as short as 2^h. n, e and u values are between ±40 mm level for some of the hours in the afternoon whereas ±5 mm level in the midnight (00:00 UT) in all the baselines for all days.

n, e and u are approximately 20, 40 and -40 mm (ISTA-BUCU) and 2, 40 and -19 mm (ISTA-TUBI) at 10-12 UT on DOY 196. Moreover, ISTA-DUMT baseline has also high values as 22, 18 and -40 mm (n, e, u), respectively, at 08-10 UT on DOY 199. TEC values are high in these time periods.

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REFERENCES / KAYNAKLAR

[1] Komjathy A., Langley R.B., "An Assesment of Predicted and Measured Ionospheric Total Electron Content Using a Regional GPS Network", ION Meeting, CA, 22-24 January 1996, 615-624.

[2] Camargo P.O., Monico J.F.G., Ferreira L.D.D., "Application of Ionospheric Corrections in the Equatorial Region for L1 GPS Users", *Earth Planets Space*, 52, 1083-1089, 2000.

[3] Warnant R., Pottiaux E., "The Increase of the Ionospheric Activity as Measured by GPS", *Earth Planets Space*, 52, 1055-1060, 2000.

[4] Skone S.H., "The Impact of Magnetic Storms on GPS Receiver Performance", *Journal of Geodesy*, 75, 457-468, 2001.

[5] Yamamoto A., Ohta Y., Okuzawa T., et.al., "Characteristics of TEC Variations Observed at Chofu for Geomagnetic Storms", *Earth Planets Space*, 52, 1073-1076, 2000.

[6] Basu S., Basu S., "Effects of Large Magnetic Storms on Communication and GPS Navigation Systems at Middle and Equatorial Latitudes", XXVIIth General Assembly of the International Union of Radio Science, Maastricht, Netherlands, 17-24 Aug. 2002.
[7] Huang C.S., Foster J.C., Erickson P.J., "Effects of Solar Wind Variations on the Mid-latitude Ionosphere", *Journal of Geophysical Research*, 107, A8, 1192, 2002.
[8] Yeh K.C., Ma S.Y., Li K.H., et.al., "Global Ionospheric Effects of the October 1989 Geomagnetic Storm", *Journal of Geophysical Research*, 99, A4, 6201-6218, 1994.
[9] Krankowski A., Baran L.W., Shagimuratov I.I., "Influence of the Northern Ionosphere on Positioning Precision", *Physics and Chemistry of the Earth*, 27, 391-395, 2002.
[10] Dach R., Hugentobler U., Fridez P., et.al., "User Manual of the Bernese GPS Software Version 5.0", Astronomical Institute, University of Bern, January 2007.
[11] Wild U., "Ionosphere and Geodetic Satellite Systems: Permanent GPS Tracking Data for Modelling and Monitoring", Achtundvierzigster Band, Vol. 48, 1994.
[12] Schaer S., "Mapping and Predicting the Earth's Ionosphere Using the GPS", Ph.D Thesis, Universitat Bern, 1999.
[13] SOPAC data center, http://sopac.ucsd.edu [Access date 05.05.2010]
[14] Skone S., Jong M.D., "The Impact of Geomagnetic Substorms on GPS Receiver Performance", *Earth Planets Space*, 52, 1067-1071, 2000.
[15] Eckl C., Snay R.A., Soler T., et.al., "Accuracy of GPS-Derived Relative Positions as a Function of Interstation Distance Observing-Session Duration, *Journal of Geodesy*, 75, 633-640, 2001.