MODELING AND FORECASTING OF TEC OBTAINED WITH IGS NETWORK OVER EUROPE

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Abstract

The monitoring and modeling ionospheric effects have been carried since 1995 by Lamkowko Satellite Observatory of Warmia and Mazury University in Olsztyn jointly with West Department of the IZMIRAN of the Russian Academy of the Sciences in Kaliningrad.

GPS measurements from 100 European IGS/EPN permanent stations were used to monitor the behaviour of the ionosphere during geomagnetic storms. A series of ionosphere maps were produced to present the spatial distribution of TEC. As the examples we analysed geomagnetic disturbances, which occurred during the month of March 2001. In this paper, diurnal variations and the latitudinal dependence of TEC over Europe for above mentioned disturbed period are presented. The TEC profiles were created from the TEC maps with a one-hour interval.

The autocovariance prediction method has been also used to predict VTEC over Onsala, Metsahovi, Hailsham, Lamkowko, Borowa Gora, Borowiec and Matera for one, two, three and four-hour ahead at a single location. The TEC time series for ionospheric quiet and disturbed conditions for years 1995 (minimum solar activity) and 2001 (maximum solar activity) at different European stations were studied to clarify the forecasting ability of this method for ionospheric purposes. Latitudes of selected stations range from 40N to 60N.

The accuracy of the method varies within reasonable limits depending on the time range of the forecast for different conditions. The forecast was compared with real data of the TEC obtained from GPS permanent observations.

1. Introduction

GPS technique has opened broad possibilities to study the TEC distribution on a regular basis. Recently, several authors used GPS networks to study TEC during storms (Baran et al., 2001, Fuller-Rowell et al., 1996, Jakowski et al., 1999, Wenninger, 1995). Those studies, in general concern the analyses of winter events during solar minimum. It was discovered that the significant positive effect was the main feature of the winter storms. Here, we present the analysis concerning the ionospheric response to the two severe geomagnetic storms of March 2001. The paper describes in particular diurnal variations and the latitudinal dependence of TEC over European sector. In this contribution, we discuss the day-to-day variation of the latitudinal TEC profiles for period of 17 to 31 March 2001. The TEC profiles were created from the TEC maps with a one-hour interval, which were produced using GPS data from 100 European IGS/EPN permanent stations. These TEC profiles also demonstrate the evaluation of the latitudinal gradients of TEC.

GPS measurements have been also used to precise forecasting of TEC for European sector using the autocovariance method. Sample of the results for the above mentioned periods are presented. The accuracy of the methods varies within reasonable limits depending on the time range of the forecast for different conditions.

The information about severe horizontal ionospheric gradients of TEC and the forecasting of TEC may be useful to ambiguity resolution in precise GPS positioning (Wenninger, 1993).

2. GPS data and estimation technique

The GPS data from IGS (International GPS Service) permanent network were used to obtain TEC changes on the global scale. A dense GPS network provided TEC measurements with high temporal and spatial resolution (Fig. 1). To present the temporal and spatial variation of TEC during the storms, we created the instantaneous TEC maps. The data from over 100 European GPS stations were used to create TEC maps. Precise dual frequency GPS phase measurements were used.

While estimating TEC, the ionosphere was approximated as a single layer at a fixed height of 400 km above the Earth's surface. The simple geometric factor was used to convert slant TEC into vertical one. A sun-fixed reference frame was used (local time/geomagnetic latitude) (Baran et al., 1997). In order to produce TEC maps, the TEC measurements from all stations were fitted to a spherical harmonic expansion as functions of geographic latitude and longitude. The maximum degree/order of the spherical expansion was 16. The maps were derived with a 15-minute resolution (Shagimuratov et al., 2002).

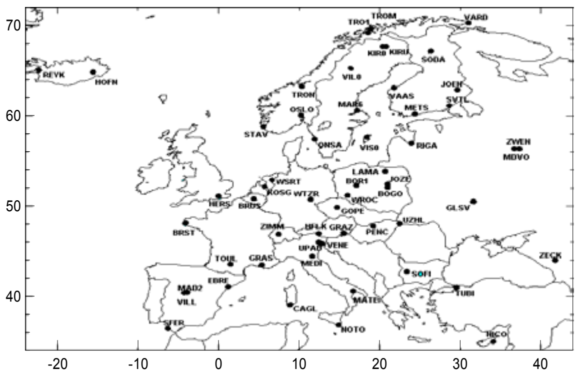


Fig.1. Geographic map of GPS stations used for retrieving TEC over Europe

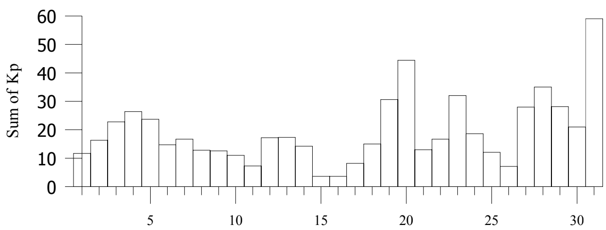


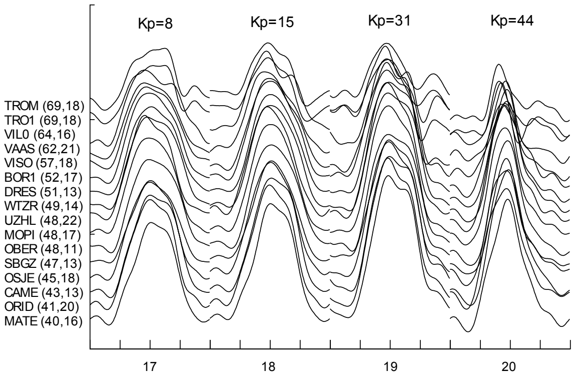
Fig.2. Variations of sum Kp during March 2001

Two great geomagnetic storms took place on 20 and 31 March. The storm on March 31st was the severest one in the last decade. The Kp index reached maximal value of 9 and ΣKp made up 60. The Dst index reached maximum magnitudes with extremely high value about -360 nT. The geomagnetic conditions during March 2001 are presented in Figure 2 as variation of sum Kp index.

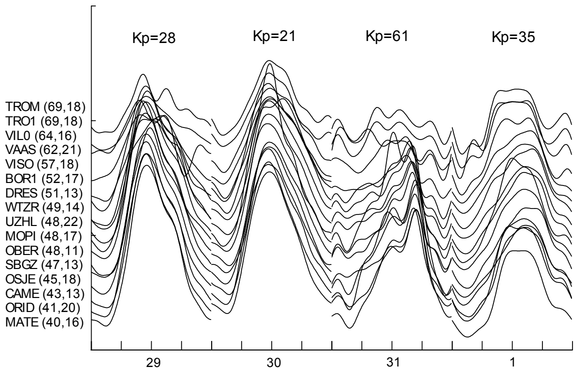
3. Response of the ionosphere to the two severe geomagnetic storms on 19/20 and on 31 March 2001

3.1. Storm-time dynamics of diurnal variations of TEC

Evaluation of diurnal variations of TEC at different latitudes during storm of 19-20 March 2001 is presented in Fig.3a. The picture demonstrates the variations of TEC over individual stations in latitude range from 40°N (down) to 70°N (top) around longitude of 20°E. The curves of diurnal variations have been shown with 5 TECU shift.



a) March 2001



b) March –April 2001

Fig.3. Diurnal variations of TEC at different latitudes during storms: a) of 19-20, b) of 31 March 2001.

For quiet period 17-18 March we can see day to day variations of TEC at different latitudes. On the first day of storm of 19 March the mark changes in TEC occurred at high latitudes. On auroral region the night enhancement of TEC is clearly highlighted. More essential changes of diurnal variations are observed at the second day of storm. During the storm the flat day-time maximum was transformed in a narrow maximum. At low latitudes the maximum is delayed about 3 hours in opposition to high latitudes.

During great storm of 31 March (Fig.3b) a diurnal variation of TEC was essentially modified against quiet time. Maximal changes in TEC behavior took place at higher latitudes. Here the day time TEC level was compared with night one. The distinct maximum appeared after noon at middle and subauroaral ionosphere. During storm night enhancement of TEC near midnight was registered at all latitudes under consideration.

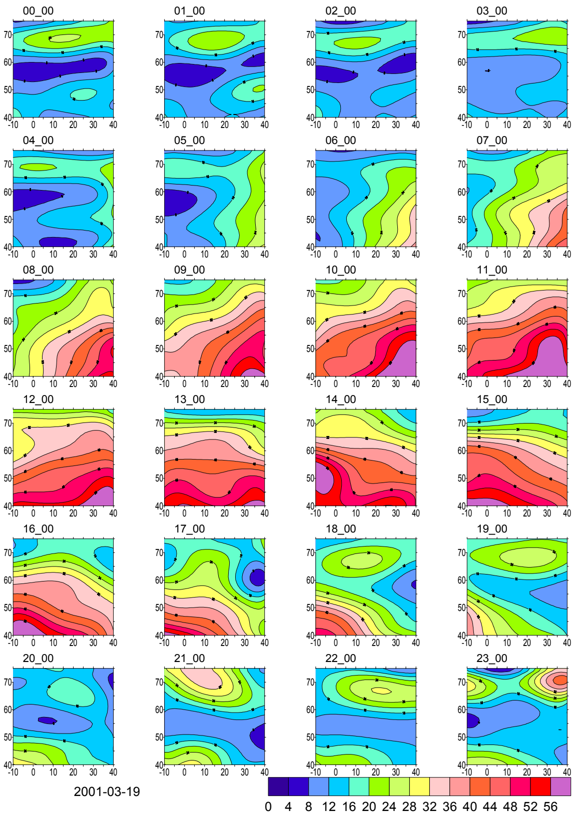


Fig.4a.The TEC maps over Europe for March 19

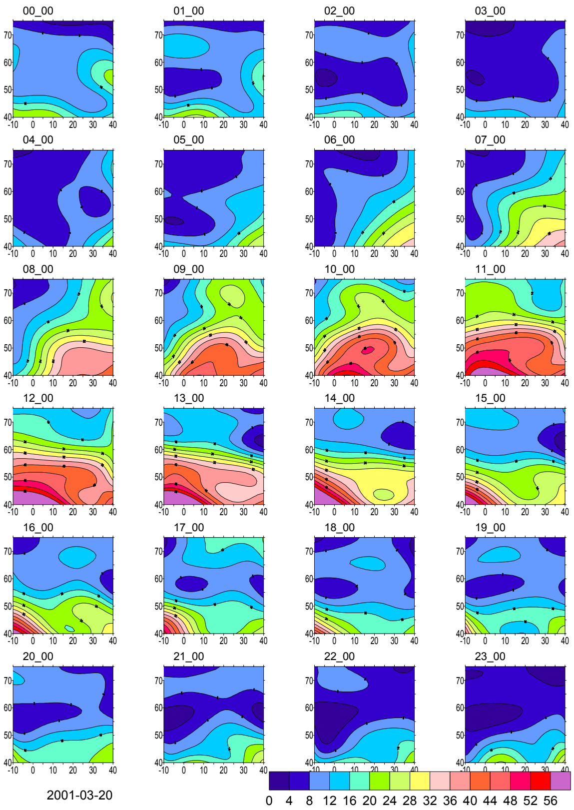


Fig.4b.The TEC maps over Europe for March 20

As an example, Figures 4a and 4b illustrate the TEC maps over Europe for 19 and 20 March 2001. A large-scale structure that can be observed in the maps as longitudinally extended depression of TEC is recognized as the mid-latitude ionospheric trough. In the maps, one may observe the temporal development of the spatial TEC distribution during the storm.

Nighttime TEC increase took place on March 19/20 at auroral and subauroral latitudes. The increase reached 100-150% in opposition to the quiet day. The positive effect occurred also at latitudes below 50°N. On March 20, after 06:00 UT the negative effect prevailed over Europe and lasted until 06:00 UT on March 21.

3.2. Latitudinal variations of TEC

Latitudinal variations characterize horizontal gradients of TEC. As known, the horizontal gradients can influence on the phase ambiguity resolution and as consequence it can deteriorate the accuracy of GPS positioning (Wanninger, 1993). For analysis of latitudinal variations of TEC we used the latitude profiles produced from TEC maps at fixed longitude. Figure 5a presents the variations of the latitude profiles over Europe at 20°E longitude for geographic latitudes from 40°N to 75°W during quiet day of 17 March 2001 (ΣKp=8). During day time the profiles demonstrate a steady slope, with a decrease of TEC towards high latitudes. The night profiles show the trough-like structure with the low level of TEC on 60-70°N latitudes. The location of trough minimum varies with time. The latitude gradients of TEC are maximal near trough. During quiet conditions the trough locates at latitudes higher than 60°N, the TEC at walls and at the bottom of the trough do not exceed ratio of 2. During disturbances the latitudinal profiles are essentially modified.

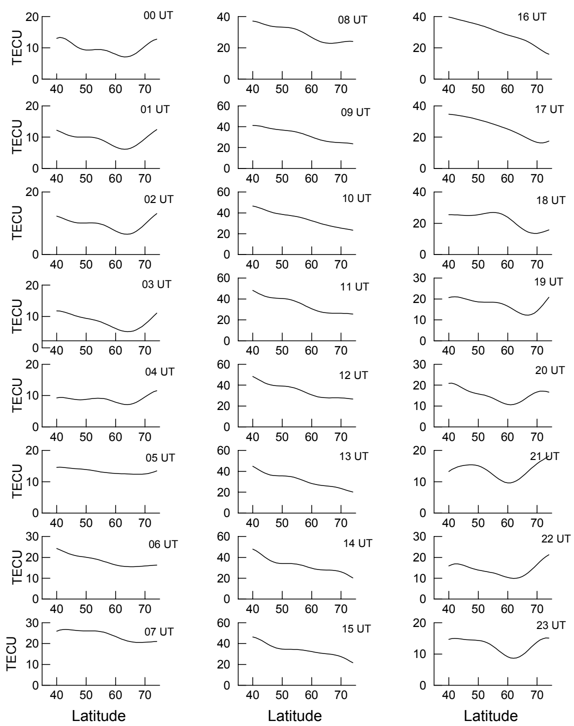


Fig 5a. Latitudinal TEC profiles on 17 March 2001 over Europe at longitude 20^0 E

Figures 5b and 5c demonstrate the behaviour of profiles during the storm days at 19 (ΣKp=34) and 31 (ΣKp=60) March 2001. During storm the trough structure can recognize even during day time. For disturbed day of 19 March the polar wall of the trough is very pronounced. The depth of trough also increases during storms. The gradients of TEC at polar wall of trough are some times higher as to quiet period. The night TEC is 2-3 bigger than during day times. The TEC increase can be attributed to particle precipitations. In contrast to 19 March during 31 March the equator wall is pronounced very much. The gradients of TEC at equator constitute one tenth of TEC on a quiet day. The TEC at the equator-side wall are 3-4 times higher that at the bottom of the trough. The behaviour of TEC profiles depends on the occurrence of the ionosphere trough. The location of trough depends on the geomagnetic activity and local time (Werner and Prolss, 1997; Wielgosz et al., 2004). During disturbances the trough has been moved to equator. During severest storm of 31 March the trough was displaced towards 50°N.

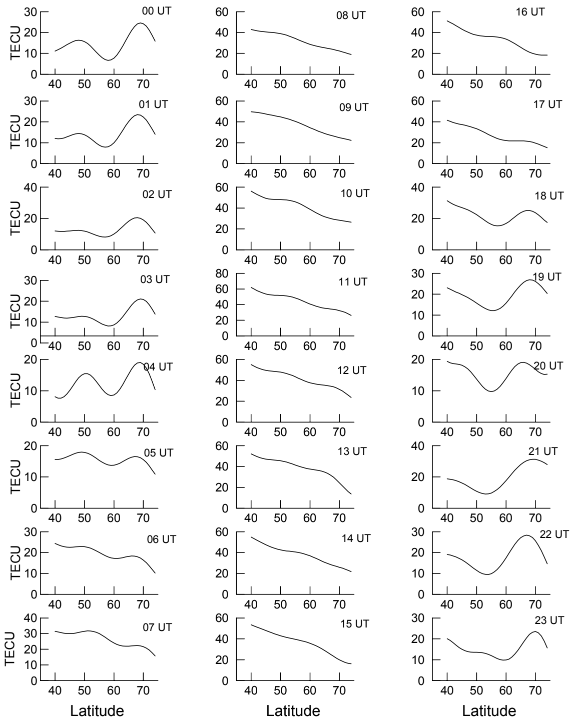


Fig 5b. Latitudinal TEC profiles on 19 March 2001 over Europe at longitude 20^0 E

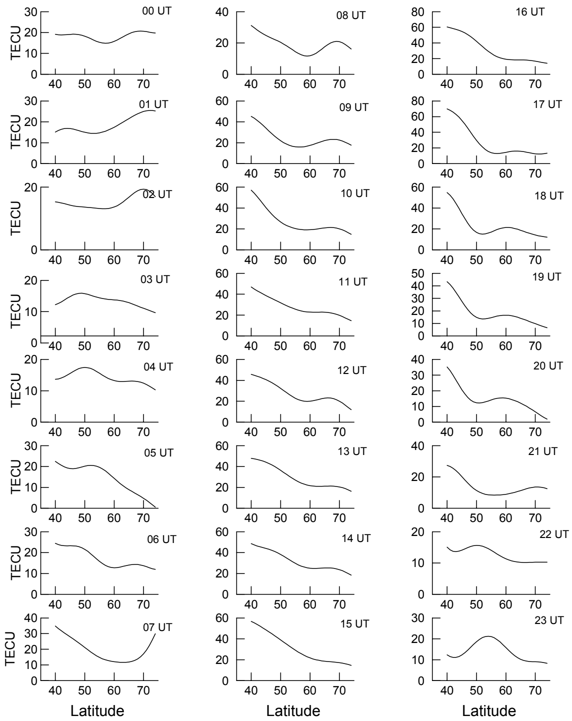


Fig 5c. Latitudinal TEC profiles on 31 March 2001 over Europe at longitude 20^0 E

6. Forecasting of TEC

In this peper, the VTEC measurements for two European IGS/EPN permanent stations, located in the same meridian: Borowiec and Matera were used to study day-to-day prediction of the TEC. The TEC forecasts were done using the autocovariance method.

In this method the first prediction point satisfies the following condition:

$$R(x_{n+1}) = \sum_{k=1}^{n-k} \left| \hat{c}_{xx}^{(n)}(k) - \hat{c}_{xx}^{(n+1)}(k) \right|^2 = \min, \qquad (1)$$

where:

$$\hat{c}_{xx}^{(n)}(k) = \frac{1}{n} \sum_{t=1}^{n-k} x_t x_{t+k}, \qquad for \qquad k = 0,\ 1,\dots,n-1, \qquad (2)$$

$$\hat{c}_{xx}^{(n+1)}(k) = \frac{1}{n+1} \sum_{t=1}^{n-k} x_t x_{t+k}, \qquad for \qquad k = 0,\ 1,\dots,n. \qquad (3)$$

The first predicted point has the form:

$$x_{n+1} = \frac{\sum_{k=1}^{n-k} \hat{c}_{xx}^{(n)}(k) x_{n-k+1}}{\sum_{k=1}^{n-k} x_{n-k+1}^2}. \qquad (4)$$

For the prediction computation, the last 50 days of the TEC values were taken. Forecasting of TEC data was calculated 1, 2, and 4 hours ahead for ionospheric quiet and disturbed conditions from March to April 2001. These results of 1, 2, and 4 hours forecasting of TEC for this station are similar to other analyzed European ones. The accuracy of the forecasting methods has been discussed in term of the mean prediction errors.

The results from autocovariance prediction method for Matera station are shown in Figures 6 – 8. For a disturbed period at maximum solar activity, such as March 16-26, 2001, the absolute values of the difference between TEC data and their 1-hour autocovariance predictions amounted to 2 TEC units (TECU). Good results of 3-hour prediction, about 6 TECU, were obtained too (Fig. 6).

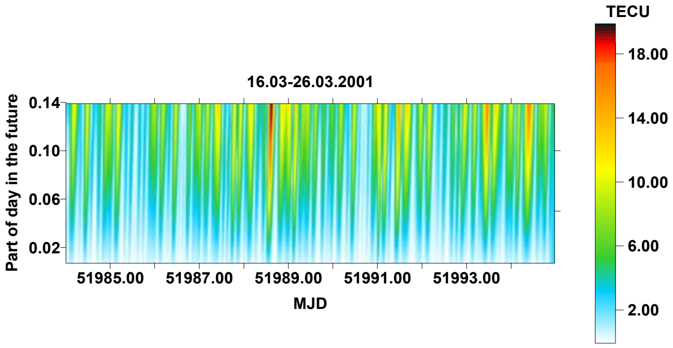


Fig. 6. The absolute values of the difference between the TEC data and their autocovariance predictions over Matera at different starting prediction epochs for March 16-26, 2001

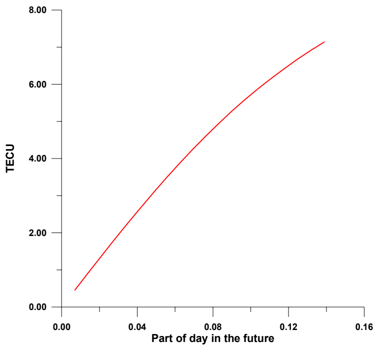


Fig.7. The mean prediction errors of the TEC data of the autocovariance predictions for March 16-26, 1997

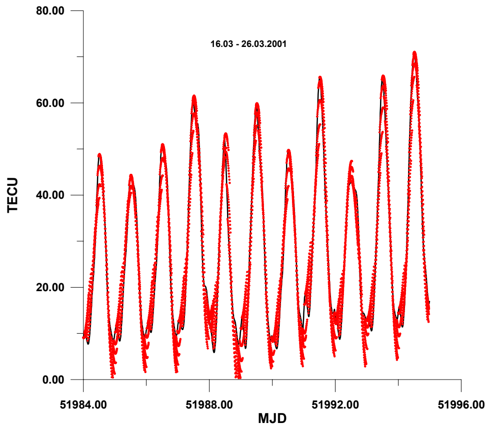


Fig.8. Four-hour ahead forecast of TEC at different starting prediction moments for March 16-26, 2001. For comparison, the real TEC data over Matera are shown (black line).

Figure 7 shows mean prediction errors of TEC data. For the 4-hour forecasts the mean prediction error is of the order of 7 TECU. A very good agreement between 1 – 4 hour ahead forecast of the TEC values and the real TEC data obtained from GPS observations are shown in Figure 8.

The results of the prediction for middle-latitude station Borowiec are shown in Figures 9–11. For a second disturbed period of high solar activity: March 27 to April 06, 2001, when the TEC values at middle-latitude station Borowiec reached the values of 60 TECU, the absolute values of the difference between the TEC data and their 1-hour and 3-hour predictions were of the order of 2 and 10 TECU, respectively (Figure 9).

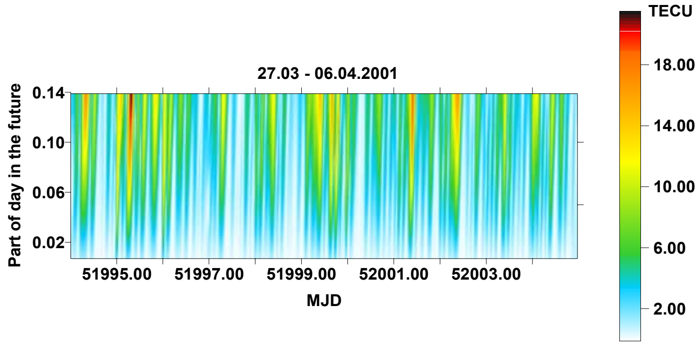


Fig.9. The absolute values of the difference between the TEC data and their autocovariance predictions over Borowiec at different starting prediction epochs for March 27 to April 06, 2001

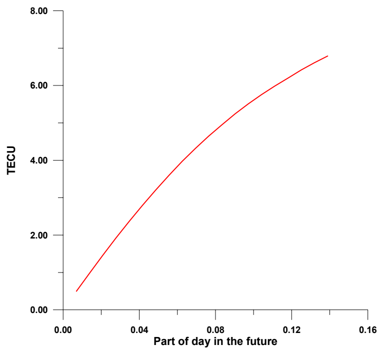


Fig.10. The mean prediction errors of the TEC data of the autocovariance predictions for March 27 to April 06, 2001

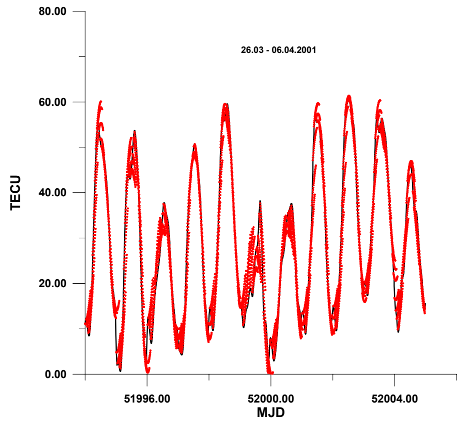


Fig.11. Four-hour ahead forecast of TEC at different starting prediction moments epochs for March 27 to April 06, 2001. For comparison, the real TEC data over Borowiec are shown (black line).

The mean prediction errors of the TEC data, shown in Figure 10, for 1-hour and 4-hour predictions reached 3 and 9 TECU, respectively.

7. Conclusion

GPS observations can provide information about the TEC distribution on a regular basis. The two severe storms began with a positive phase. The maximum positive effect took place at auroral and subauroral ionosphere. The strong increase of TEC at high latitudes can be attributed to the particle precipitation. The high deviation of TEC relative to quiet conditions gave rise to the displacement of the minimum of the midlatitude through.

The analyses of the TEC latitudinal profiles over Europe were carried out during solar maximum for disturbed conditions. The latitudinal gradients reach its maximum during the night hours. During the disturbances the latitudinal dependence is more variable. We relate this effect to the migration of the position of the trough minimum, which depends on the geomagnetic activity.

The autocovariance forecasting method of the TEC provides an acceptable accuracy especially during the geomagnetic storms. This method is very simple and do not need any information a-priori about the process as well as additional inputs, such as the solar or magnetic activity indices.

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