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Influence of the 27-day solar flux variations on the ionosphere parameters measured at Irkutsk in 2003–2005

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Abstract

We present an investigation of the influence of the 27-day solar flux variations, caused by solar rotation, on the ionosphere parameters such as the F2 layer critical frequency (foF2) and the total electron content (TEC). Our observational data were obtained with the Irkutsk Digisonde (DPS-4) located at 52.3 North and 104.3 East during the period from 2003 to 2005. In addition, we use TEC data from the Global Ionosphere Maps (GIM) based on Global Positioning System (GPS) satellites. The solar radiation flux at a wavelength of 10.7 cm (F10.7 index) is used as an index characterizing the solar activity level. A good correlation between observed ionosphere parameters and solar activity variations is found especially in autumn-to-winter season. We estimate the impact of the 27-day solar flux variations on the day-to-day variability and determine the time delay of the ionosphere response.

Keywords: Quasi-27-day solar flux variations; Day-to-day ionosphere parameters variability; DPS-4 ionosonde

1. Introduction

Day-to-day variations of the ionosphere parameters are caused by different factors, among which are solar activity, geomagnetic activity, and meteorological conditions. Under different conditions, one of these factors can play the major or secondary role, usually variability is mainly attributed to geomagnetic and meteorological activity (Rishbeth and Mendillo, 2001; Forbes et al., 2000). Nevertheless, the authors of these papers point out that under some conditions the solar radiation flux can be a major contributor to the day-to-day variability of foF2.

Since 2003 the regular ionospheric observations have been performed at Irkutsk (52.3N, 104.3E) with the modern DPS-4 ionosonde (Reinisch et al., 1997). The regular character of the observations enables us to investigate the character of ionosphere parameter variations and to study the influence of geomagnetic disturbances and solar activity on the ionosphere. The analysis of the day-to-day foF2 variations obtained at Irkutsk showed a good correlation between the observed daily mean critical frequencies and daily F10.7 index values for winter months (Oinats et al., 2006). This fact has motivated us to research the influence of the 27-day solar flux variations on the ionosphere parameters.

27-day variations of solar flux are caused by the solar rotation and many papers have been devoted to studying the influence of these variations on the ionosphere state (Ivanov-Kholodny and Nikolsky, 1969; Akasofu and Chapmen, 1972; Jakowski et al., 1991). However, many other factors can mask the 27-day modulation of local ionosphere parameters. Sufficiently clear correlation with the 27-day solar flux variations have been found only for total electron content values (Titheridge, 1973). At the same time, research of the influence of the 27-day solar flux variations on the local ionosphere parameters has a practical significance for the improvement of present global ionosphere models such as International Reference Ionosphere (Bilitza, 2001).

In the present paper, we carry out a detailed analysis of the influence of the 27-day solar flux variations on the ionosphere parameters measured with the Irkutsk Digisonde

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in 2003–2005, such as critical frequency of F2 layer (foF2) and total electron content (DPS-TEC). The DPS-TEC was calculated by the extrapolation above a F2 layer peak height using the Reinisch–Huang method (Reinisch and Huang, 2001). The validation of the method showed that TEC obtained by Digisonde and incoherent scatter radar are in very close agreement except for magnetically disturbed day, and results of Digisonde and satellite TEC measurements generally agree within 2–4 TECU (Reinisch and Huang, 2001). TEC values were also obtained from the Global Ionosphere Maps (GIM) of the vertical TEC that are obtained from Global Positioning System (GPS) satellite measurements and that allowed us to compare DPS- and GIM-TEC values with each other. For our analysis we selected GIM calculated at Jet Propulsion Laboratory of California Institute of Technology (JPLG) (http://www.jpl.nasa.gov/).

2. DPS data

To exclude the influence of traveling ionosphere disturbances (TID) the observational data were averaged over four diurnal intervals: morning 5–9 LT, noon 11–15 LT, evening 17–21 LT and night 23–3 LT. Thus, four initial data sets were obtained corresponding to four parts of day for each ionosphere parameter. For example, in Fig. 1, the noon values of foF2 and DPS-TEC are shown by thick curves and F10.7 index values are shown by thin curve for 2003. As we can see, solar flux index and ionosphere parameters undergo variations with a ~27-day period that are related with each other.

3. Comparison between DPS- and GIM-TEC data

The comparison shows that TEC data obtained with the DPS-4 and from GIM are well correlated. However, on the average GIM-TEC values exceed DPS-TEC values by 1.5–2 times. The regression GIM-TEC (DPS-TEC) mass plot is presented in Fig. 2 by grey circles for noon. As we can see, it is well approximated by a linear dependency. The approximate linear functions for the GIM/TEC-DPS/TEC regressions for different parts of the day (also presented in Fig. 2 by solid lines) are:

Noon: GIM-TEC = 1.24* DPS-TEC + 4.48 (rms = 2.4%)
Evening: GIM-TEC = 1.57* DPS-TEC + 5.54 (rms = 4.1%)
Night: GIM-TEC = 1.89* DPS-TEC + 3.09 (rms = 1.7%)
Morning: GIM-TEC = 1.42* DPS-TEC + 2.18 (rms = 2.1%)

The greatest difference between GIM- and DPS-TEC values is observed at night, when GIM-TEC is greater than DPS-TEC in almost 2 times. The difference decreases at noon but it remains very high. The difference between GIM- and DPS-TEC attributable to the plasmaspheric contribution should be about 2 TECU in average for Irkutsk latitude (Lunt et al., 1999). Belehaki et al. (2004) found that the regression coefficient between GPS- and DPS-TEC is about 1.0 that disagrees with our findings. In our opinion, the disagreement with both Lunt et al. (1999) and Belehaki et al. (2004) is most likely associated with small number of GPS ground stations in Eastern Siberia and, respectively, with inaccuracy in reconstruction of absolute TEC values in GIM. At the same time according to small rms the TEC variations are reconstructed well enough.

4. Method of analysis

To estimate the impact of the 27-day solar flux variations onto variations of the ionosphere parameters correlation functions were calculated between foF2 (or DPS-TEC, or GIM-TEC) and F10.7 index. The correlation functions were calculated based on 27- and 81-day sample lengths (R27 and R81) and for time shift changing from −13 to 13 days. The expression for the calculation of the correlation functions in our case is

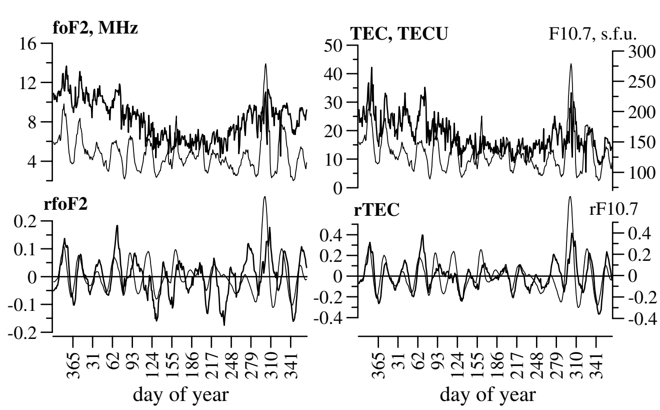

Fig. 1. Example of the initial data sets used in correlation analysis in 2003. Noon 4-hour average values of foF2 (left) and TEC (right) are shown on the top panels by thick curves. Thin curves correspond to F10.7 index. Noon relative 27-day variations rfoF2 (left) and rTEC (right) calculated by formulas defined in the text are shown on the bottom panels. Thin curves on the bottom figure correspond to rF10.7 values.

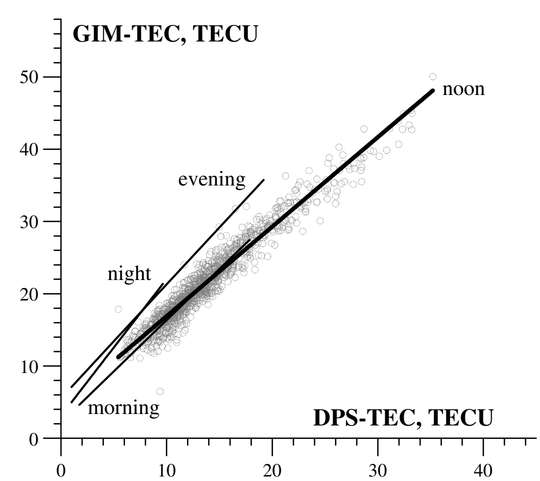

Fig. 2. Regression lines of GIM-TEC on DPS-TEC values for four diurnal intervals indicated on the figure and scatterplot GIM-TEC (DPS-TEC) (shown by grey circles) for noon.

$$Rm(i,\tau) = \frac{1}{\sigma_{X(i)}\sigma_{Y(i-\tau)}}\left(\overline{X(i)Y(i-\tau)} - \overline{X(i)}\cdot\overline{Y(i-\tau)}\right),$$

where X and Y are the data sets, m is the sample length, i is a number of the sample central value in the full data set, τ – time shift and $\sigma_{X(i)} = \sqrt{\overline{X(i)^2} - \overline{X(i)}^2}$ is a root mean square deviation (rms). "Overline" means arithmetic mean, for example, $\overline{X(i)} = \frac{1}{m}\sum_{k=1}^{m} X(i - \frac{m}{2} + k)$. The correlation coefficients R_{max} corresponding to the 0.05 significance level (confidence probability 95%) can be estimated using critical values of Student's distribution for the given sample lengths. R_{max} equals to 0.38 and 0.22 for 27- and 81-day sample lengths accordingly. It is assumed that R27 and R81 values exceed R_{max} for periods of significant correlation.

As we mentioned above, the DPS-TEC and GIM-TEC sets are well correlated and corresponding correlation functions negligibly differ from each other. Therefore, the results only for DPS-TEC are presented. As an example, annual variations of the correlation function maximum $\max_{-13\leqslant\tau\leqslant 13} Rm(i,\tau)$ and of the correlation coefficient $Rm(i,0)$ (value of correlation function without time shift) are shown in Fig. 3 by thick and thin curves accordingly for noon of 2003–2005. Correlation coefficient R_{max} is shown by dashed line.

For more precise estimation of the time delay between the 27-day solar flux and the ionosphere parameter variations during the periods of significant correlation the relative 27-day variations of foF2, DPS-TEC (rfoF2, rTEC) and F10.7 index (rF10.7) were also calculated by formulas

$$\text{rfoF2} = \frac{\langle\text{foF2}\rangle_9 - \langle\text{foF2}\rangle_{81}}{\langle\text{foF2}\rangle_{81}},$$

$$\text{rTEC} = \frac{\langle\text{TEC}\rangle_9 - \langle\text{TEC}\rangle_{81}}{\langle\text{TEC}\rangle_{81}},$$

$$\text{rF10.7} = \frac{\langle\text{F10.7}\rangle_9 - \langle\text{F10.7}\rangle_{81}}{\langle\text{F10.7}\rangle_{81}}.$$

Brackets "$\langle\,\rangle$" mean the smoothing by the running average method with 9- and 81-day time windows. Thus, all variations with periods smaller than 9 days and greater than 81 days were excluded from rfoF2, rTEC, and rF10.7. For example, on the bottom of Fig. 1 the relative variations are shown for 2003. As we can see the relative variations of the ionosphere parameters and of F10.7 index are well related during some periods of 2003, but the relative variations of the ionosphere parameters lag behind for about several days. Fig. 4 shows the annual variations of R81 correlation coefficients between the relative variations of the ionosphere parameters and of F10.7 index as well as corresponding time delays τ for noon. Thick curve shows the maximum of the correlation function and thin curve corresponds to the value of the correlation function without time shift. On the right of Fig. 4, the examples of the distributions of the time delay $n\tau(\%)$ are shown for the shaded periods of significant correlation. The maximum of the

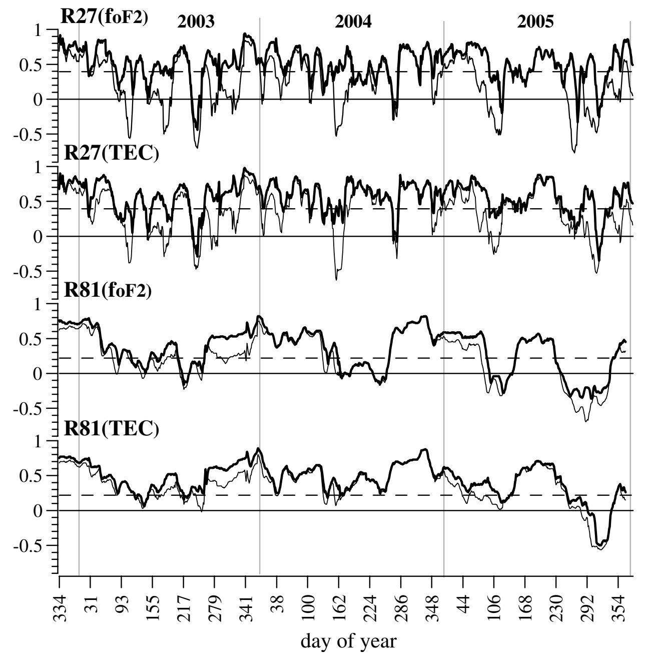

Fig. 3. Annual variations of correlation function maximum $\max_{-13\leqslant\tau\leqslant 13} Rm(i,\tau)$ (thick curves) and correlation coefficient $Rm(i,0)$ (thin curves) between noon ionosphere parameters indicated in parenthesis (foF2 or TEC) and F10.7 index in 2003–2005. Top two panels correspond to 27-day and bottom to 81-day sample lengths. The correlation coefficient of the 0.05 significance level (confidence probability is 95%) is shown by dashed lines.

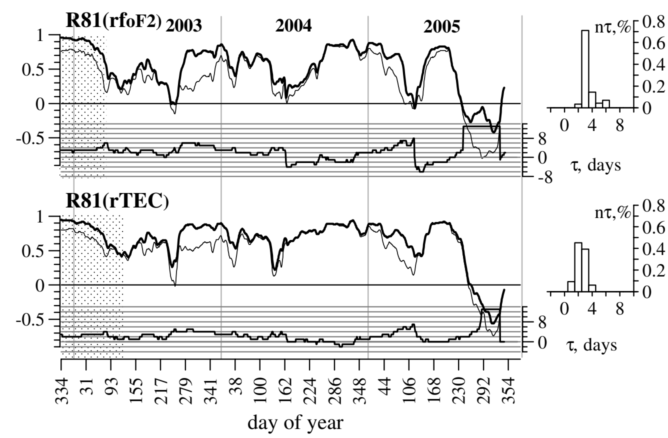

Fig. 4. Annual variations of correlation function maximum $\max_{-13\leqslant\tau\leqslant 13} R81(i,\tau)$ (thick curve), correlation coefficient $R81(i,0)$(thin curve), and time delay τ (bottom curve) between relative 27-day variations rfoF2 for noon (top panel) and rF10.7 in 2003–2005. Time delay distribution $n\tau(\%)$ corresponding to the stable correlation period (marked by shading on the figure) is shown on the right of the panel. The maximum of the $n\tau(\%)$ distribution corresponds to the most abundant time delay value during the period. The bottom panel shows the same as the top one but for relative 27-day variations rTEC and rF10.7.

$n\tau(\%)$ distribution corresponds to a most abundant time delay during the period.

Moreover in the assumption of the linear dependency between the ionosphere parameters and F10.7 index the relative variations allow us to estimate a rough linear regression coefficient **k** (rfoF2 = **k** · rF10.7, rTEC = **k** · rF10.7) for periods of significant correlation.

5. Results and discussion

As shown in Fig. 3, the R27 correlation function values are averagely greater than R_{max}; therefore, correlation between the ionosphere parameters and the solar flux variations is significant. However, there are many specific abrupt falls corresponding to periods of the weak correlation. Such falls prevent from finding long time intervals of the stable correlation but at the same time, they allow us to suppose about the reasons of its appearance. Indicated falls particularly can be related with the increase of the geomagnetic activity at corresponding days of the year. Fig. 5 shows the time dependencies of the R27 correlation function maximums for the ionosphere parameters foF2 and TEC (grey curve) and for their relative variations rfoF2 and rTEC (black curve). The bottom diagram shows the Ap index that characterizes the global geomagnetic activity. As we can see in Fig. 5, some correlation falls concur with the geomagnetic activity peaks (it is especially evident for correlation functions of the relative variations). For example, increased geomagnetic activity (Ap = 108) causes the sufficient decrease of foF2 and the worsening of the correlation at day 150, 2003 (see also Fig. 1). The weakening of the 27-day solar flux variations can also cause the common worsening of the correlation at the end of 2005. The weakening of the 27-day solar flux variations is a feature of the periods of the solar activity minimum (and maximum) during the 11-year solar cycle when active formations on the sun almost disappear (and vice versa, when there are many of them). It is also obvious from Fig. 5 that the number and depth of the falls for the foF2 correlation function are greater than for the TEC correlation function.

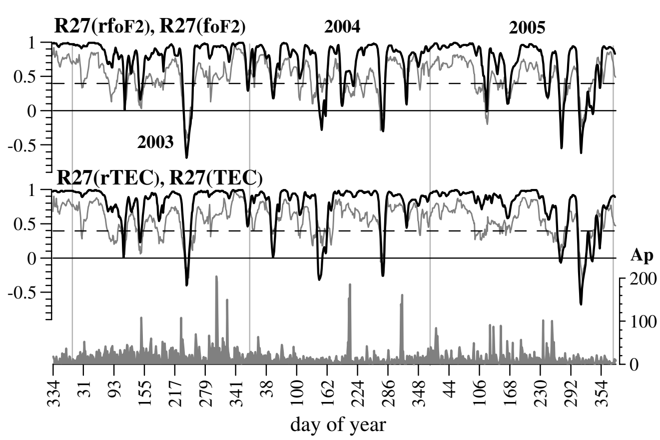

Fig. 5. Comparison of the correlation function maximum based on 27-day sample lengths and geomagnetic activity variations. Variations of correlation function maximum $\max_{-13\leqslant\tau\leqslant13}R27(i,\tau)$ between rfoF2 and rF10.7 (black line) and between foF2 and F10.7 (grey line) are shown on the top panel. The same variations for rTEC and TEC are shown on the lower panel. Geomagnetic activity variations (Ap index) are shown on the bottom of figure.

The R81 correlation functions are smoother than R27. In Fig. 3 for noon, the periods of the stable correlation between the ionosphere parameters and the solar flux variations are obvious. They are mainly located in autumn and winter seasons (except 2005). There are stable correlation periods also in middle summer (for example, in 2003 and 2005), but they are brief and its correlation function values are smaller. Correlation for TEC is stronger than for foF2 since the duration of the stable correlation periods is averagely greater and the correlation function values are higher.

Because of the R81 correlation functions are smoother than R27, we used 81-day samples for estimation of the time delay between the ionosphere parameters and the solar flux variations. In Fig. 4, the time delay changes into the range from about −5 to about 8 days but the most abundant time delay is averagely equal to 2–4 days. Such values of the time delay are in agreement with results of other authors (Jakowski et al., 1991). The most abundant time delay is negative in summer of 2005. Seemingly, the effect of other factors together with the solar activity may cause the obtained negative values. For example, the joint influence of the solar and geomagnetic activities may result in this "non-physical" effect. The average linear regression coefficients are equal to ~0.35 and ~0.7 for foF2 and TEC accordingly. The time delay and the regression coefficients have no any seasonal regularity.

Figs. 6 and 7 present the combined data of the correlation analysis based on 81-day samples during the observational period. Grey bars correspond to periods of the stable correlation ($R > R_{max}$). The figures show the maximal and average correlation coefficient ($\mathbf{r_m}$ and **r**), the time duration in days (**T**), the most abundant time delay in days between ionosphere parameters and solar flux variations ($\boldsymbol{\tau}$), and the average linear regression coefficient (**k**) for each period. The shaded bars correspond to the periods of stable correlation with duration lower than 54 days. The average correlation coefficient reaches the values of 0.62 and 0.57 for foF2 and TEC accordingly at noon. The maximal correlation coefficient is equal to 0.82 for foF2 and to 0.89 for TEC. Thus, the impact of the solar flux variations on the day-to-day variability of the ionosphere parameters is equal to about 35%, but can reach 80% in maximum, with regard to other effecting factors.

As we can see, the best correlation is found at noon. For other day parts the number of the stable correlation periods, their time duration and average correlation coefficients decrease. The worst correlation is observed at night. The stable correlation periods are located mainly in autumn-to-winter season at all day parts except night and some times also in summer (2005 and 2003).

Correlation between TEC and F10.7 are noticeably stronger than between foF2 and F10.7 that is in agreement with results of Jakowski et al. (1991). For example, the stable correlation between TEC and F10.7 is found at noon during almost all observational period (with average correlation coefficient equal to about 0.55). This fact can be

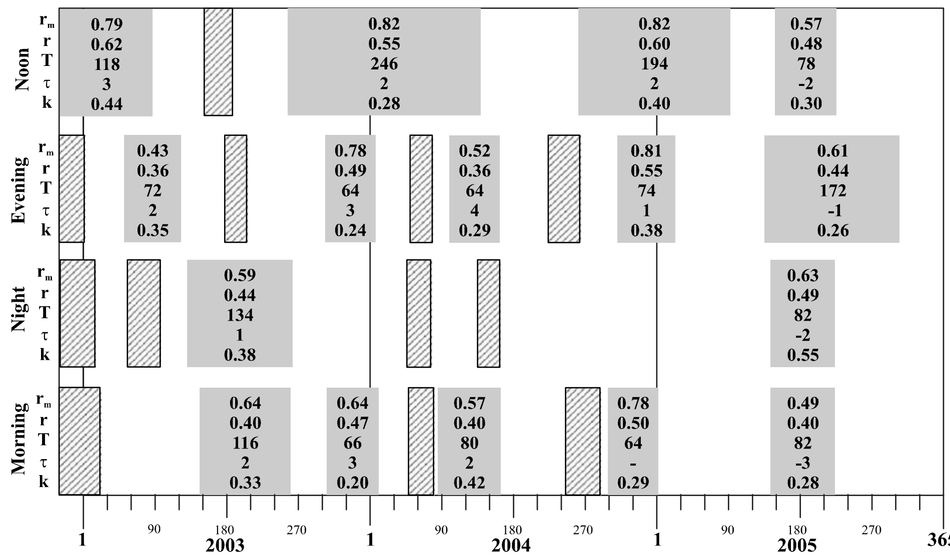

Fig. 6. Schematic illustration of foF2 correlation analysis results for four diurnal intervals in 2003–2005. The grey rectangles correspond to periods of year when significant correlation is observed. The values of maximal and average correlation coefficient (**r_m** and **r**), time duration in days (**T**), most abundant time delay in days between foF2 and F10.7 variations (τ), and average linear regression coefficient (**k**) are indicated for each period. The shaded rectangles correspond to periods of significant correlation with duration lower than 54 days.

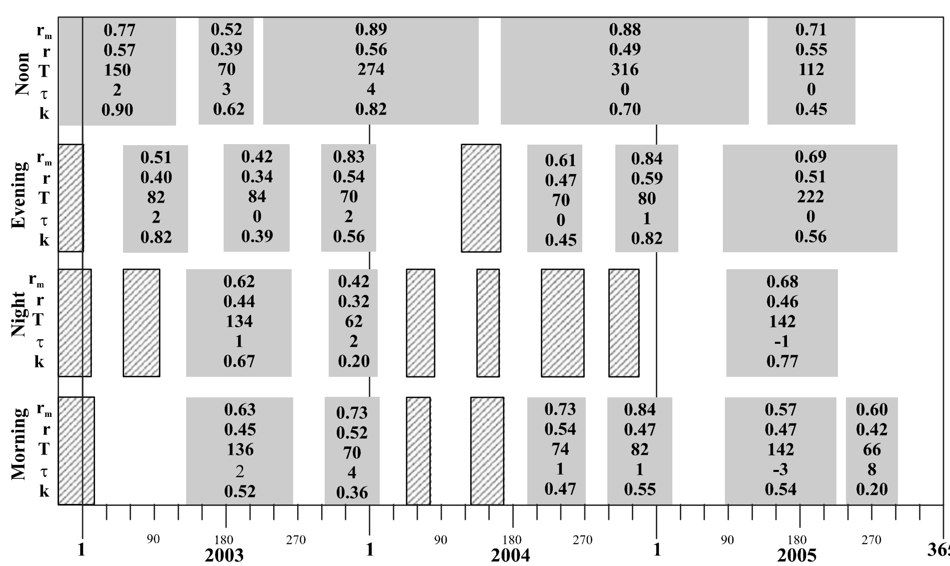

Fig. 7. The same as Fig. 6, but for TEC data.

explained by the stronger influence of the geomagnetic and meteorological activities on the lower then the upper ionosphere.

The analysis showed that coefficients of correlation between the ionosphere parameters and the solar radiation flux and the durations of the stable correlation period are noticeably higher in winter compared with summer. This agrees with results of Titheridge (1973) and Richards et al. (1994) and can be explained by different level of the solar activity control of ionospheric processes for different seasons (King, 1966). In a manner, our results are contrary to Rishbeth (1993), who found a little correlation between NmF2 and F10.7 for November–December, 1979. The reason of the disagreement can be associated with the high solar activity level and short analysis period in the case of his studies.

6. Conclusion

27-day variations of foF2 and TEC caused by the solar flux modulation are distinctly observed with the Irkutsk sounder.

DPS-TEC values are noticeably less then GIM-TEC ones. The difference exceeds estimations obtained by Lunt et al. (1999) and Belehaki et al. (2004). In our opinion, this disagreement is most likely associated with small number of GPS ground stations in Eastern Siberia and, respectively, with inaccuracy in reconstruction of absolute TEC values in GIM. Nevertheless, the correlation functions between DPS-TEC and F10.7 index and between GIM-TEC and F10.7 index are in the good agreement.

Correlation analysis between foF2 (and TEC) and F10.7 based on the 27-day sample length showed that the geomagnetic activity can depress the influence of the 27-day solar flux variations on the ionosphere parameters.

Correlation analysis based on the 81-day sample length showed, that the best correlation between variations of the ionosphere parameters and F10.7 solar index is observed in Irkutsk in autumn-to-winter season. The brief correlation periods are found also in summer of 2003 and 2005, but the correlation function values are smaller than in autumn and winter. The best correlation is found at noon and the worst at night.

The maximal correlation coefficient for foF2 can reach to 0.82 that corresponds to the solar activity contribution to the day-to-day variability equal to $\sim$70%. In general, TEC variations have more long-range periods of good correlation and the greater correlation coefficients then for foF2. The maximal correlation coefficient for TEC can reach to 0.89 (contribution is equal to $\sim$80%). The time delay between variations of the ionosphere parameters and F10.7 solar index is equal to 2–4 days.

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