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Enhanced variability in the topside ionosphere

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Abstract

Variability of total electron content (TEC) observed by the Faraday rotation method at Florence has been studied with the same technique applied independently to the ionospheric parameters f_0F_2 and $M(3000)F_2$ of the ground-based vertical-incidence sounding database (VID). Results of daily and monthly TEC disturbance indices at sub-ionospheric point are compared with variability of the ionosphere at Rome and Gibilmanna (deduced from VID) for a period of 1976 to 1991. During moderate and high solar activity the variability of TEC is greater than the variability of VID, whereas during solar minimum the situation is opposite. In this context joint TEC and VID observations distinguish either the *F* region peak or the topside ionosphere heights where the dynamic processes dominate at different times.

Key words *ionosphere – total electron content – vertical-incidence sounding – disturbance indices*

1. Introduction

Different data sources are able to yield information on ionosphere variability. Among those the most representative is the vertical-incidence sounding database (VID) providing the disturbance indices from an hourly to annual long-term scale (Gulyaeva, 1994). However, this source is restricted in the altitude range to the peak height of the F_2 region. Attempts have been made to estimate percentage deviations of topside sounding and incoherent scatter peak parameters from regional meta-median (Gulyaeva *et al.*, 1994; Gulyaeva, 1995). The regional meta-median was taken as the median value among a set of local monthly medians (in the PRIME mid-European area or the Scandinavian region) then percentage deviation from meta-median of the topside ionosonde measurements or the incoherent scatter EISCAT *F*-region peak ionization was evaluated for each time of observation. However, two of the latter sources yielded information discontinuous on time and space.

The ground-based ionosonde observations of electron density profiles show a growing variability with height towards the F_2 peak (Mosert de Gonzales and Radicella, 1995). Such electron density variability may be attributed to the increasing role of dynamic processes with height (Mikhailov, 1994). However at which heights do these processes dominate?

Total electron content (TEC) measurements could provide the most comprehensive database to define the degree of the ionospheric disturbance throughout the ionospheric heights continuous in time for the sub-ionospheric point (Leitinger, 1992). The Faraday rotation measurements made at Florence (Spalla and Ciraolo, 1994) were used for this purpose in the present study.

Faraday rotation measurements are affected by an ambiguity of n semicycle, as it is impossible to know how much polarization turns during propagation through the ionosphere. As the rotation of polarization is proportional to the TEC and inversely proportional to the square of the frequency, it is easy to solve the ambiguity during low solar activity when the TEC is very low: in fact a 136 MHz signal usually turns about 1 semicycle at night minimum. On the contrary, during high solar activity the TEC could be so high that the rotation of the polarization is more than 1 semicycle. There are some methods to solve this problem (Davies, 1980). While these considerations could affect the absolute values of TEC, their relative variability for the particular month determined regarding the monthly median does not suffer from that shortcoming.

2. Data analysis

One of the largest TEC databases in Europe was used for the analysis. It includes the Faraday rotation data measured at Florence from 1975 to 1991 calibrated for uncertainty (Spalla and Ciraolo, 1994). Hourly values of TEC were analysed similarly to vertical-incidence sounding database (VID) to produce hourly negative and positive disturbance indices characteristic of deviation from the TEC monthly median (Gulyaeva, 1994).

Figure 1 presents, as an example, the diurnal variation of percentage deviation of measured TEC values from the monthly median (solid lines, right scale) for three days in October 1977. The relevant negative (bottom section) and positive (top section) ionospheric disturbance indices *Dm*– and *Dm*+ (left scale) are shown by horizontal lines for each hour. The first day presents a case of negative disturbance (01.10), the second day (08.10) is an example of a quiet day (within 20% of deviation from monthly median), and the third day (15.10) is a heavy positive ionospheric storm detected by TEC data.

The hourly TEC negative *Dm*– and positive *Dm*+ disturbance indices are represented by the same system of weights taken for the ionosonde peak parameters percentage deviations from the monthly median. They differ from the ionosonde indices by absence of de-

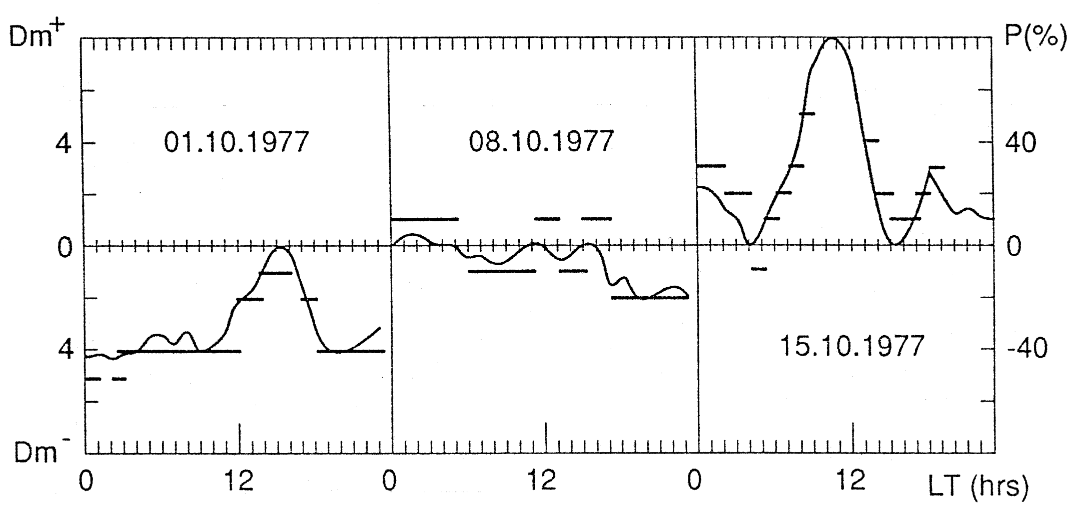

Fig. 1. Hourly percentage TEC deviation from the monthly median (solid line, right scale) and produced negative and positive disturbance indices (horizontal lines, left scale) for 3 days in October 1977: negative disturbance (01.10), quiet day (08.10) and positive storm (15.10).

Table I. Monthly and annual TEC negative and positive disturbance indices from observations at Florence. Monthly values $Dm\times10$, annual values $Dm\times100$. 0 = absent observations.

Y		1	2	3	4	5	6	7	8	9	10	11	12	Y
75	*Dm*–	0	0	0	0	0	0	0	0	0	13	13	11	127
	Dm+	0	0	0	0	0	0	0	0	0	12	15	15	140
76	*Dm*–	11	0	0	16	14	14	15	12	0	0	0	0	140
	Dm+	13	0	0	17	15	16	19	14	0	0	0	0	156
77	*Dm*–	0	0	0	0	0	0	0	0	20	22	0	0	210
	Dm+	0	0	0	0	0	0	0	0	24	18	0	0	210
78	*Dm*–	0	19	0	20	26	25	0	0	22	21	21	26	227
	Dm+	0	31	0	22	22	24	0	0	36	25	30	34	273
79	*Dm*–	27	26	21	0	0	0	0	19	25	22	24	25	235
	Dm+	29	25	16	0	0	0	0	29	26	17	24	29	217
80	*Dm*–	24	20	0	22	23	24	23	0	0	0	0	18	222
	Dm+	28	26	0	20	17	20	20	0	0	0	0	22	220
81	*Dm*–	23	21	0	22	26	23	27	0	0	0	0	27	234
	Dm+	34	27	0	25	28	20	27	0	0	0	0	25	243
82	*Dm*–	27	26	0	25	26	22	35	27	0	0	0	0	253
	Dm+	33	23	0	25	28	24	30	24	0	0	0	0	249
89	*Dm*–	0	0	0	0	28	20	29	27	28	32	25	26	254
	Dm+	0	0	0	0	23	18	28	22	28	29	31	28	253
90	*Dm*–	24	29	12	0	24	22	22	19	18	22	29	25	232
	Dm+	30	33	16	0	24	22	25	28	18	23	34	28	259
91	*Dm*–	23	0	0	0	28	33	29	23	24	28	31	0	265
	Dm+	32	0	0	0	24	32	26	25	24	24	34	0	262

scriptive and qualifying letters with TEC data so the TEC indices always indicate degree of percentage deviations of measured TEC values from TEC monthly median. As soon as hourly values of the TEC disturbance measure are obtained, the larger temporal period indices, such as 3 h, daily, monthly and annual indices, can be calculated from these. Monthly and annual values of TEC derived indices are presented in table I. These can be compared with the relevant VID disturbance indices based on ionosonde observation at Rome and Gibilmanna. Results of VID ionospheric indices for Rome based on data of maximum usable frequency MUF3000 (table II) and f_0F_2 critical frequency (table III) readily demonstrate that the variability of MUF in most cases is greater than the variability of f_0F_2 because MUF data involve both effects of the F_2 layer critical frequency and the peak height through the $M3000F_2$ relation (Bilitza *et al.*, 1979). Table III for Rome and table IV for Gibilmanna present indices characterising some local differences in the Mediterranean region.

Table II. Monthly and annual VI sounding negative and positive disturbance indices at Rome based on MUF(3000)F_2 data. Monthly values $Dm\times10$, annual values $Dm\times100$.

Y		1	2	3	4	5	6	7	8	9	10	11	12	Y
76	*Dm*−	17	20	20	21	23	21	21	21	17	18	17	18	195
	Dm+	18	22	23	23	23	20	21	21	22	24	21	25	218
77	*Dm*−	18	19	19	20	21	20	20	21	23	22	21	19	202
	Dm+	23	21	19	24	21	22	20	20	21	22	21	22	213
78	*Dm*−	21	20	21	25	25	22	21	20	20	20	22	22	216
	Dm+	24	20	21	22	21	19	19	20	20	21	23	23	211
79	*Dm*−	22	20	22	25	23	23	21	22	22	20	19	18	214
	Dm+	21	22	22	25	23	20	19	21	21	20	17	21	210
80	*Dm*−	16	16	14	16	16	18	17	14	18	15	18	15	161
	Dm+	19	14	12	14	13	14	13	14	14	15	18	17	147
81	*Dm*−	17	16	15	22	20	16	19	15	15	17	20	18	174
	Dm+	18	15	14	19	15	15	15	16	13	15	20	18	159
82	*Dm*−	17	17	19	19	21	20	22	19	23	18	17	17	191
	Dm+	19	19	15	17	18	17	20	17	19	17	17	20	178
83	*Dm*−	17	19	21	19	18	21	19	20	20	18	19	18	190
	Dm+	20	20	19	19	18	18	18	20	20	20	23	22	197
84	*Dm*−	17	19	20	19	18	19	21	18	19	19	17	18	186
	Dm+	20	20	17	18	19	20	20	19	20	19	19	21	195
85	*Dm*−	19	18	17	18	18	19	19	17	16	19	17	16	177
	Dm+	20	17	18	20	17	19	20	18	17	18	18	20	186
86	*Dm*−	15	20	16	16	20	18	19	18	17	16	16	16	173
	Dm+	20	17	17	17	20	20	19	18	17	18	19	20	185
87	*Dm*−	15	15	15	16	17	18	19	20	19	17	15	16	168
	Dm+	22	18	17	17	16	20	21	19	20	19	18	22	191
88	*Dm*−	17	17	16	18	17	19	17	16	18	16	17	16	169
	Dm+	19	17	17	15	17	16	17	17	18	15	18	18	170
89	*Dm*−	15	19	21	21	19	17	14	20	18	18	16	15	179
	Dm+	16	15	15	16	15	15	14	16	17	16	19	17	160

3. Results

Figure 2 presents daily TEC and VID indices, averaged for different seasons of each year of observation. Successive seasons are: 1 = winter (January, February, November and December), 2 = spring (March and April), 3 = summer (May to August), 4 = fall (September and October). Results are given for TEC observations (circles), Rome VID data (solid line) and Gibilmanna (crosses). Negative indices are shown in the bottom section, positive disturbance measure in the top section. While Rome and Gibilmanna show synchro-

Table III. Monthly and annual VI sounding negative and positive disturbance indices at Rome based on critical frequency f_0F_2. Monthly values $Dm\times10$, annual values $Dm\times100$.

Y		1	2	3	4	5	6	7	8	9	10	11	12	Y
76	*Dm*–	17	16	19	18	23	20	19	17	16	18	15	18	180
	Dm+	21	22	22	21	23	20	19	20	22	22	20	24	211
77	*Dm*–	18	18	18	18	19	20	18	19	20	21	20	17	187
	Dm+	22	19	20	22	21	20	19	20	20	21	21	22	205
78	*Dm*–	20	18	21	24	24	20	20	20	18	20	24	21	208
	Dm+	24	21	21	20	20	19	17	20	21	22	29	24	214
79	*Dm*–	20	22	21	24	23	22	21	21	21	20	21	20	213
	Dm+	22	22	22	25	22	20	20	21	22	18	18	21	210
80	*Dm*–	16	15	12	16	16	17	16	13	17	14	16	15	152
	Dm+	19	15	13	13	12	13	12	13	13	13	18	17	143
81	*Dm*–	15	15	13	23	19	16	19	14	14	15	22	20	175
	Dm+	18	15	13	16	15	13	15	15	12	14	18	18	154
82	*Dm*–	17	16	17	17	18	20	21	18	21	17	16	17	178
	Dm+	20	18	13	16	16	16	19	16	17	16	17	21	171
83	*Dm*–	16	19	19	18	17	19	17	18	19	18	20	17	185
	Dm+	20	19	18	19	17	17	17	19	19	20	22	21	194
84	*Dm*–	16	18	19	18	17	17	18	17	18	18	15	16	178
	Dm+	20	21	16	18	18	20	19	17	20	18	18	20	191
85	*Dm*–	17	16	16	17	16	18	17	14	15	18	15	15	166
	Dm+	20	16	16	19	17	18	18	16	17	18	18	21	184
86	*Dm*–	14	19	16	15	20	15	17	16	15	15	14	16	159
	Dm+	19	16	16	15	19	18	18	17	16	17	19	19	176
87	*Dm*–	15	16	14	18	18	32	18	19	17	17	15	15	169
	Dm+	22	19	18	19	17	29	20	17	19	18	17	23	197
88	*Dm*–	16	16	15	16	15	17	16	14	17	15	18	15	164
	Dm+	19	16	16	14	17	16	16	16	17	14	17	17	168
89	*Dm*–	15	20	19	20	19	16	14	18	17	17	16	15	173
	Dm+	16	13	14	14	15	13	14	15	16	15	19	17	151
90	*Dm*–	15	18	17	18	16	18	15	16	13	15	17	14	161
	Dm+	18	19	17	17	14	13	15	16	15	14	18	15	156
91	*Dm*–	15	15	16	18	22	21	19	18	17	21	22	15	183
	Dm+	18	19	13	13	14	17	16	18	15	15	18	17	160

Table IV. Monthly and annual VI sounding negative and positive disturbance indices at Gibilmanna for critical frequency f_0F_2. Monthly values $Dm \times 10$, annual values $Dm \times 100$. 0 = missed observations.

Y		1	2	3	4	5	6	7	8	9	10	11	12	Y
76	*Dm–*	0	0	0	18	22	19	21	19	16	18	18	17	181
	Dm+	0	0	0	19	23	20	22	22	22	23	21	22	214
77	*Dm–*	16	17	18	21	19	19	19	18	19	19	18	17	184
	Dm+	22	20	21	23	22	23	23	20	19	21	21	24	213
78	*Dm–*	19	19	21	21	22	21	19	21	19	17	20	19	198
	Dm+	22	22	20	17	20	23	19	22	20	18	22	23	207
79	*Dm–*	0	0	0	0	0	24	20	21	18	18	21	21	209
	Dm+	0	0	0	0	0	18	22	23	18	19	23	27	217
80	*Dm–*	18	24	0	0	0	0	0	0	0	0	0	0	210
	Dm+	24	25	0	0	0	0	0	0	0	0	0	0	245
83	*Dm–*	0	0	0	0	0	0	0	0	0	0	18	16	170
	Dm+	0	0	0	0	0	0	0	0	0	0	21	19	200
84	*Dm–*	17	17	17	16	16	18	17	17	18	17	16	15	167
	Dm+	18	19	18	18	19	20	19	19	19	21	18	18	187
85	*Dm–*	17	17	16	17	17	19	19	17	15	17	15	15	168
	Dm+	19	17	17	22	18	20	22	17	18	19	18	20	189
86	*Dm–*	15	0	0	0	20	17	16	17	16	14	15	14	158
	Dm+	20	0	0	0	18	20	19	18	17	17	19	19	182
87	*Dm–*	14	15	14	16	17	16	16	17	15	15	17	15	157
	Dm+	20	18	16	20	18	20	21	18	19	16	18	19	183
88	*Dm–*	16	16	17	19	18	19	19	18	17	14	15	16	170
	Dm+	17	17	17	16	15	14	15	14	21	21	18	16	169
89	*Dm–*	15	18	18	16	0	0	0	0	0	0	0	0	189
	Dm+	17	16	14	16	0	0	0	0	0	0	0	0	173
90	*Dm–*	15	18	16	14	16	17	15	15	13	16	17	15	162
	Dm+	20	17	14	13	14	12	13	13	15	14	18	17	156
91	*Dm–*	15	15	16	19	18	20	17	16	0	21	20	14	175
	Dm+	20	17	13	14	15	16	14	15	0	13	17	16	159

nised disturbances, the TEC variability differs significantly from the VID results.

These differences are seen more clearly in fig. 3 representing the monthly ionospheric indices of TEC (table I) and Rome (table II). Here the negative indices (bottom section) and positive indices (top section) are presented for the sub-ionospheric point of TEC observation (about 40N, 07E) and VID indices at Rome (42N, 12.5E). Clear dominant TEC disturbances are seen for moderate and high solar activity during 1978, ..., 1982 and for 1989 to 1991. However their ratio is opposite for the solar minimum when the VID indices are

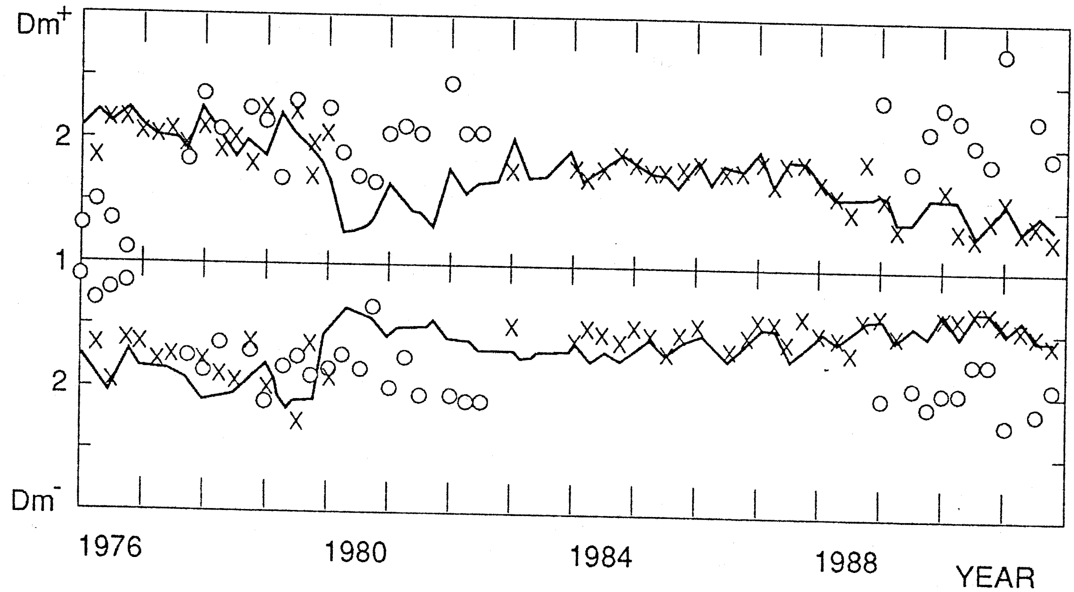

Fig. 2. Diurnal ionospheric disturbance indices averaged over different seasons for each year. 1 = winter (months 1, 2, 11, 12); 2 = spring (months 3, 4); summer (months 5,6,7,8); fall (months 9,10). Ionosonde results at Rome (solid line) and Gibilmanna (crosses), TEC data at Florence (circles). Positive disturbance indices (top section), negative indices (bottom section).

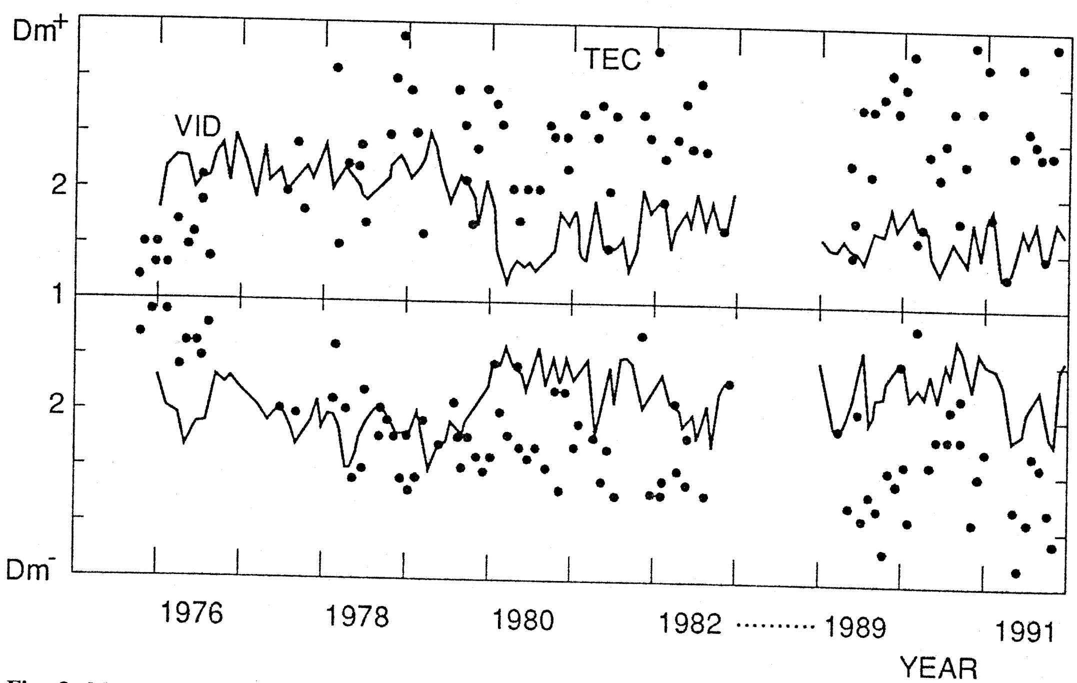

Fig. 3. Monthly ionospheric negative and positive disturbance indices based on vertical-incidence data (VID) at Rome and TEC measurements at Florence for 1975 to 1991.

Table V. Diurnal mean negative and positive TEC disturbance indices under different conditions during 1975-1991.

	Dm–	*Dm+*	Days
Spring	1.81	1.97	238
Summer	1.92	1.94	636
Autumn	1.85	1.97	280
Winter	1.90	2.19	471
Days 1-5	1.90	2.03	1154
Days 6-7	1.86	1.99	471
Total	1.89	2.02	1625

greater than TEC indices during 1975-1977.

Table V lists the results of TEC daily negative and positive disturbance indices, averaged for the whole TEC database. Only those days when the TEC measurements lasted at least 12 h per day were considered (total 1625 days for 1975 to 1991). Daily disturbance indices were combined for four different seasons as above in fig. 2 but for all years 1975 to 1991, and also for 5 working days (Monday to Friday) each week and weekend (Sunday and Saturday).

4. Discussion and conclusions

Regarding all results we can state that positive TEC disturbances are greater in magnitude than the negative disturbances. It is quite understandable because negative percentage deviations from monthly median cannot exceed 100% by definition while positive disturbances for individual days can be as high as 400% (Gulyaeva, 1995). The results of table V show that magnitudes of positive TEC disturbances are often greater than 100% of deviation from the median, the greatest negative disturbances being observed in winter and summer. Positive disturbances are dominant in winter and are probably recorded by the Westerbork interferometer system (Spoelstra, 1995). Regarding the absence of clear solar cycle dependence of the Westerbork TID variation, this can be explained by dominating TEC disturbances during the high solar activity and reversal of this ratio towards the solar minimum.

Indeed, TEC variability presents total ionosphere variability up to about 2000 km. Since the electron density profiles in the bottomside ionosphere show increasing variability with height (Mosert de Gonzales and Radicella, 1995), one could expect that when TEC disturbance indices are greater than the VID indices, this means enhanced variability in the topside ionosphere as compared with the *F* region peak height. The F_2 region peak heights grow with the solar cycle (Shapiro, 1985) from about 300 km at solar minimum to about 400 km at solar maximum during daytime at mid-latitudes. Hence, we can conclude that during the solar maximum dynamic processes are dominant in the topside ionosphere heights above 400 km. On the contrary, greatest variability occurs at or below the *F* region peak height for the solar minimum.

Since the ionosphere variability recorded with Westerbork radar can be attributed to TIDs occurring at any altitude of the atmosphere, the Westerbork data at the different phases of the solar cycle show TIDs occurring either in the topside ionosphere or in the bottomside ionosphere and/or lower atmosphere up to the troposphere (Spoelstra, 1995). To distinguish actual heights of enhanced ionosphere variability, combined ground-based ionosonde, TEC and Westerbork observations are helpful. In so doing, the ionosonde should be located near the Westerbork system while the TEC observation site should be chosen so that the Westerbork falls near the sub-ionospheric point for TEC observations.

One more conclusion follows from the TEC data analysis presented in table V. While the diurnal, monthly, seasonal, solar cycle, altitudinal and similar dependences present natural environmental processes of the disturbances, the analysis made for 5 working and 2 weekend days per week is intended to disclose some technogenous impact on the ionosphere. The TEC data show greater variability in the ionosphere during five working days compared with weekends. This seems to confirm possible industrial sources of such disturbances (Popov *et al.*, 1995). Further analysis must be extended with a broader database worldwide. At the same time, it is necessary to carry out a study on the variability of radio signals induced by industrial sources, in order to distinguish the two different effects.

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