VARIATIONS OF THE TOTAL ELECTRON CONTENT OF THE IONOSPHERE OVER KAZAKHSTAN REGION DEPENDING ON SOLAR ACTIVITY

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A. Nowadays transionospheric radio sounding by applying the signals of Global Positioning System (GPS) permits a continuous monitoring of the terrestrial ionosphere [1-3]. The so-called GIM technology (Global Ionospheric Maps), which was developed by some research centers (JPLG, the USA; CODE, Switzerland, and others), is a powerful tool for monitoring and investigation of the global and local structure of ionosphere [1,4-6].

In this paper the variations of total electron content from 1999 to 2013 in the Kazakhstan region based on GIM cards (Global Ionospheric Maps) was studied. The behavior of the total electron content was compared with the variations of critical frequency of the ionospheric layers F2, f_0F2, which were obtained by ionosond in Almaty. Critical frequency f_0F2 is a measure of the ionization maximum electron density. The values of the total electron content I(t) were calculated with use of IONEX maps in the GIM for [42.5°N; 75.0°E], the closest point to location of the city Almaty [43.25°N; 76.92°E]. In the paper the GIM-maps, which are developed by Swiss research center CODE (Center for Orbit Determination in Europe, University of Berne, Switzerland) based on data from more than 150 GPS signal reception centers were used. The GIM-maps are available online in the IONEX format (ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex). The vertical total electron density was calculated with consideration of condition of the social-geomagnetic conditions based on spherical harmonic formulas [1,2,7]. TECU – the universally accepted measure of the total electron content (total electron content unit), eq. 10^{16} el/m^2.

Table 1 – Annual average values of solar activity index $F_{10.7}$ and levels of solar activity

Years	Annual average values $F_{10.7}$	Levels of solar activity
1999	153,7	High $F_{10.7}$>150
2000	179,5	
2001	181,5	
2002	179,5	
2003	128,8	Medium (phase of downturn of SA) $F_{10.7}$=100÷150
2004	106,5	
2005	91,7	Low (the deepest minimum of SA for last 100 years) $F_{10.7}$<100
2006	80,0	
2007	73,1	
2008	69,0	
2009	70,6	
2010	80,1	
2011	113,4	Medium (phase of growth of and abnormal low maximum of SA) $F_{10.7}$=100÷150
2012	119,9	
2013	122,8	

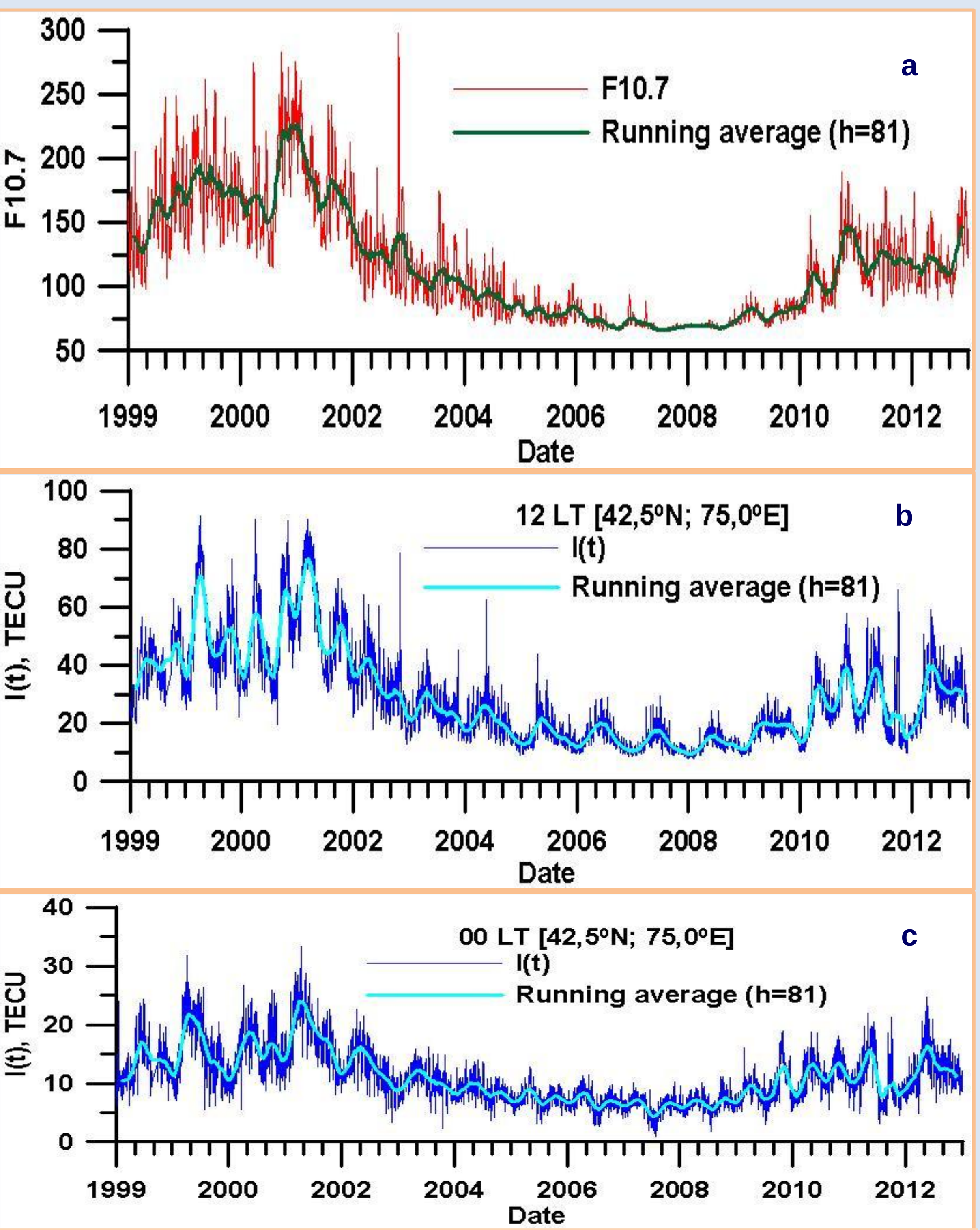


Figure 1 – The variations of radio emission solar flux F10.7 (**a**), midday (**b**) and midnight (**c**) variations of the total electron content I(t), calculated with the use of the IONEX-maps in GIM for[42.5°N; 75°E] for period of time 1999-2013

B. The studied period (1999-2013) covers different levels of solar activity. In figure 1a (the red curve) diurnal variations of the solar activity index and solar radio emission flux with the wave-length 10.7 cm, $F_{10.7}$.were shown. The information was obtained from the web-side of the Space Weather Prediction Center (SWPC) of US National Oceanic and Atmospheric Administration (NOAA) http://www.swpc.noaa.gov. The dark green curve in figures 1a is their running average with an 81-day time step. The studied period covers different stages of the solar activity: maximum (1999-2002), when solar radio flux $F_{10.7}$ was more than 150; medium $F_{10.7}$=100÷150 (2003-2004 – phase of downturn of the solar activity); minimum $F_{10.7}$<100 (2005-2010), which fall at the deepest minimum of solar activity for last 100 years, especially 2007-2009; medium $F_{10.7}$=100÷150 (2011-2013 – phase of growth of the solar activity and abnormal low maximum of the solar activity). The current developing of the 24th solar activity cycle is similar to developing of low solar activity cycle [8]. As the figure 1 shows, the last maximum of the solar activity (2000-2002) was notably higher – $F_{10.7}$~180. The table 1 gives the annual average values of solar activity index $F_{10.7.}$ There are shown different levels of solar activity for the investigated period.

The variations for the period 1999-2013 of the midday and the midnight variations of the total electron content I(t), which were calculated based on the IONEX-maps in the GIM ground point [42.5°N; 75°E], are given in the figures 1b and 1c. The blue curve in the figures 1b and 1c is their running average with an 81-day time step.

The variations of midday (a) and midnight (b) values of critical frequencies of the F2 layer, f_0F2, according to the data of the ionosonde in Almaty [43.25°N; 76.92°E] for the period from 1999 to 2013 are given in figures 2a and 2b. The blue curve in the figures 2a and 2b is their running average with an 81-day time step.

The variations of the total electron content *I(t)* and of the electron density in the maximum of F2 layer "track" the changes in the solar activity. The annual average of midday and midnight values of the total electron content I(t) and critical frequency F2, f_0F2, are shown in the table 2.

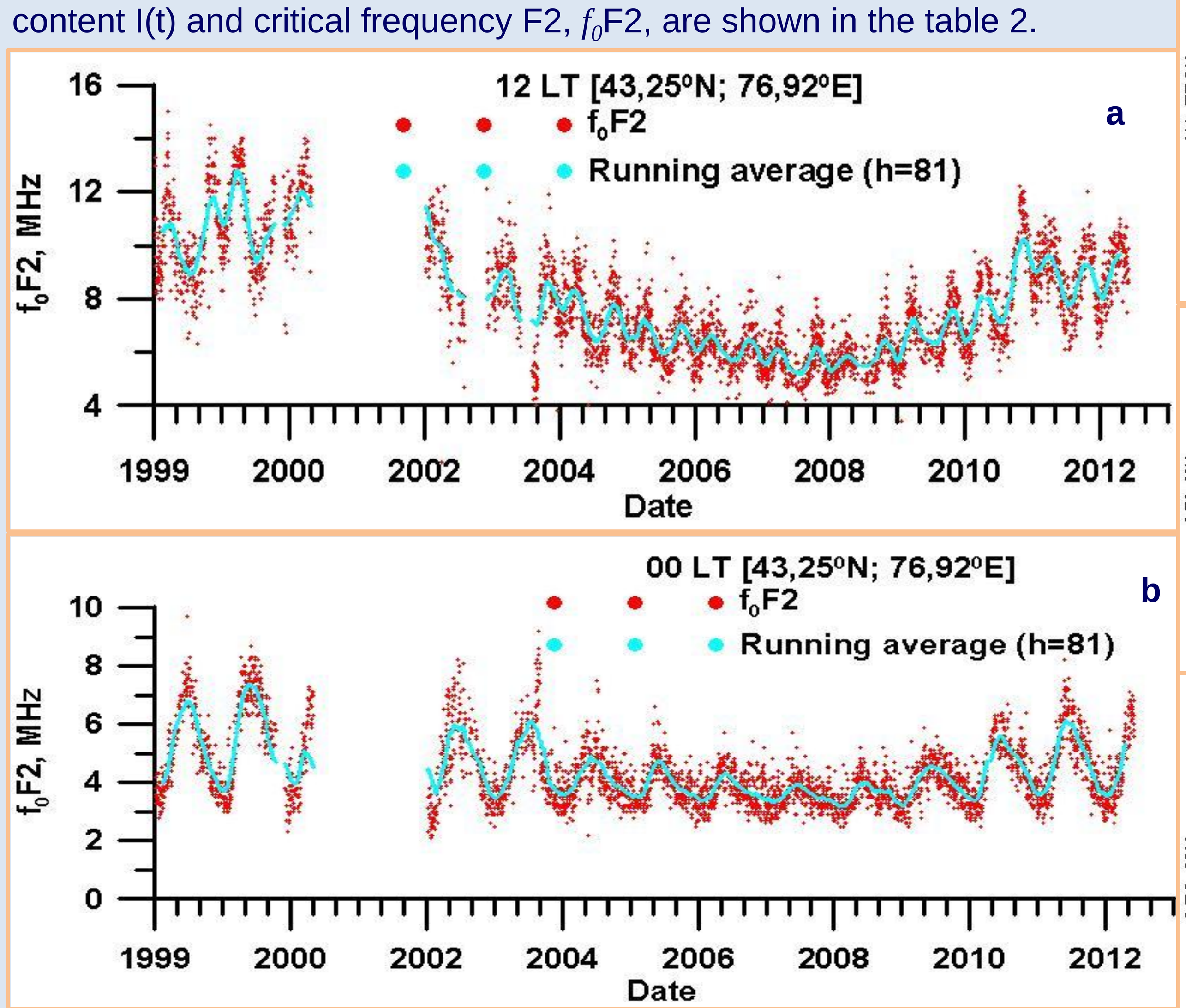


Figure 2 – Variations of midday (a) and midnight (b) values of critical frequencies of the F2 layer, f_0F2, according to the data of the radiosond in Almaty [43.25°N; 76.92°E] for the period from 1999 to 2013

C. The annual midday average values of total electron content I(t) decrease approximately 5 times, from 63,1 TECU in the solar activity maximum (1999) to 12,7 TECU in the solar activity minimum (2009). The annual midday average values of critical frequency of F2 layer, f_0F2 decrease approximately 2 times, from 11,9 MHz in the solar activity maximum (2001), to 5,7 MHz in the solar activity minimum (2008).

The annual midday average values of the total electron content I(t) decrease approximately 3 times, from 18,3 TECU in the solar activity maximum (2002) to 6,1 TECU in the solar activity minimum (2008). The annual midnight average values of critical frequency decrease approximately 1,6 times, from 5,8 MHz in the solar activity maximum (2000) to 3,6 MHz in the solar activity minimum (2009). In the solar activity maximum (2000) the midnight average values of the total electron content and critical frequency F2, f_0F2 were equal to the same values in period of the solar activity minimum (2008, 2009) - (15 3) TECU and (6,3 1,5) MHz. This linear connection is especially noticeable on curves, drawn with 81-day time step.

Table 2 – Annual average values of midday and midnight values of the total electron content I(t) and critical frequency of layer F2, f_0F2

Years	Annual average values			
	I(t), TECU		f_0F2, MHz	
	12 LT	00 LT	12 LT	00 LT
1999	63,1	13,2	10,3	5,0
2000	50,6	15,9	10,9	5,8
2001	50,1	15,4	11,9	4,9
2002	56,3	18,3	No data	No data
2003	33,2	12,7	9,2	4,6
2004	24,4	10,3	8,2	4,6
2005	20,1	8,7	7,4	4,1
2006	16,1	7,5	6,6	3,9
2007	15,2	6,9	6,2	3,7
2008	13,2	6,1	5,7	3,6
2009	12,7	6,5	5,8	3,6
2010	17,9	9,2	6,8	4,0
2011	27,9	11,3	8,2	4,5
2012	25,3	10,6	8,9	4,7
2013	31,1	12,6	9,2	4,7

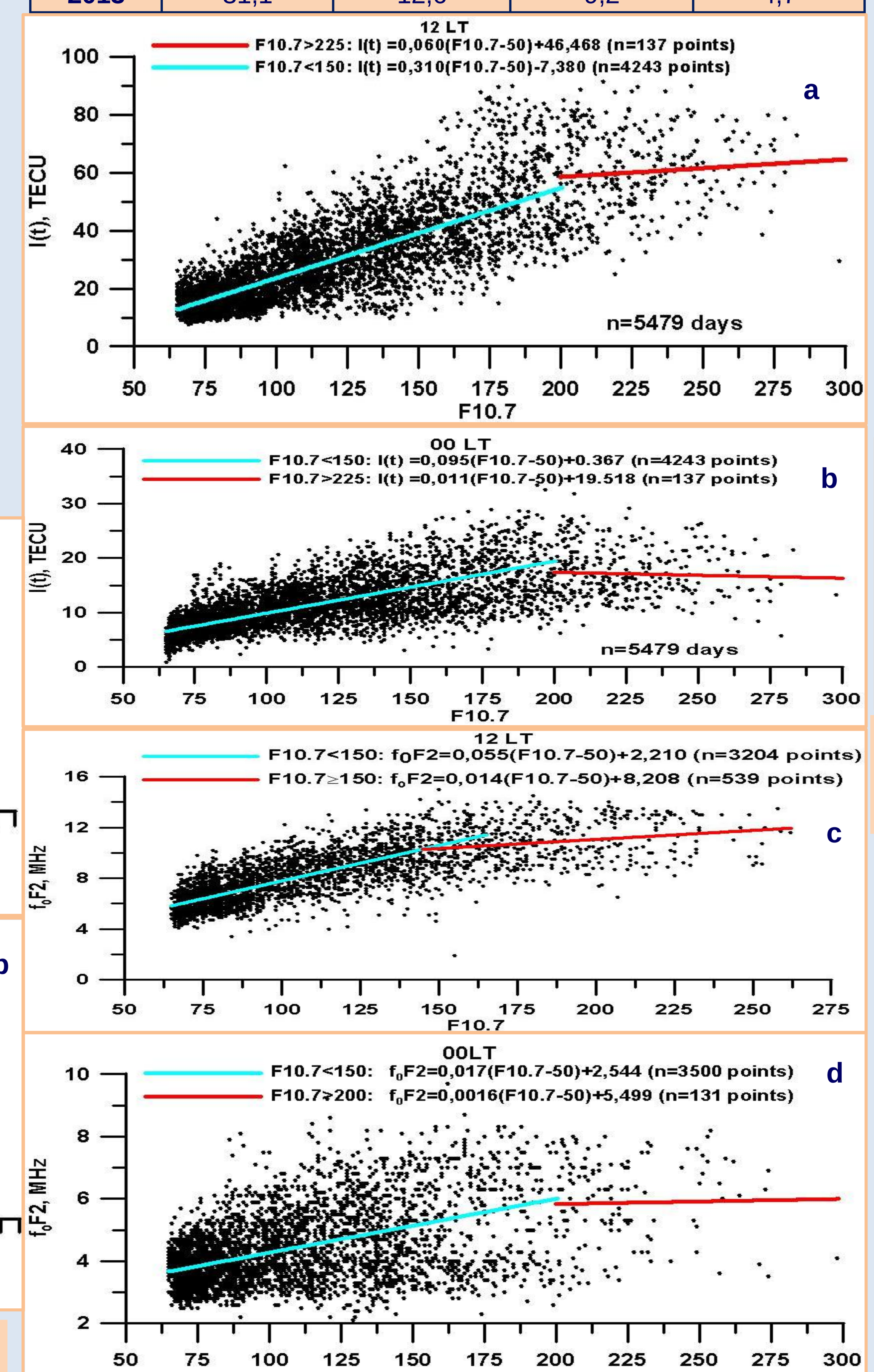


Figure 3 – Regressional dependencies on midday (**a**) and midnight (**b**) values of the total electron content I(t) and regressional dependence of midday (**c**) and midnight (**d**) values of critical frequency of F2 layer, f_0F2, on the solar activity values

D. Regressional dependencies of midday and midnight values of the total electron content I(t) and the critical frequency F2, f_0F2 on the solar activity values in the period from 1999 to 2013 are given in the figure **3a**, **b**, **c** and **d**.

Over the range of F10.7 <150 the positive correlation is observed, which can be defined as linear function of the form $y = \mathbf{b_1}x+\mathbf{b_0}$. Starting from the values of F10.7>(150÷200) units dependence of total electronic content on F10.7 weakens again (after increase of values of F10.7 growth of TEC values practically stops). Over the range $F_{10.7}$<150 the values of the root-mean-square deviations, σ, of the I(t) parameter: σ=~17 for midday conditions and σ=~7 for midnight conditions; f_0F2: σ=~1,4 for midday conditions and σ=~0,8 for midnight conditions. Over the range $F_{10.7}$>150 there's a huge dispersion. We have found the tendency of the ionosphere saturation under high values of $F_{10.7}$ based on registration data of the Faraday effect, obtained during acquisition of signal of the geostationary earth-orbiting satellite «ETS-II» by the «Orbita» station Almaty (43,2°N; 76.9°E) during the period from September 1985 to the December 1989 [9]. The results are in the concordance with papers [1, 7, 10, 11], where also are given the results of analysis of long time-series of geophysical parameters.

E. The diurnal variations of the absolute values of the total electron content during the periods of abnormal low Solar activity

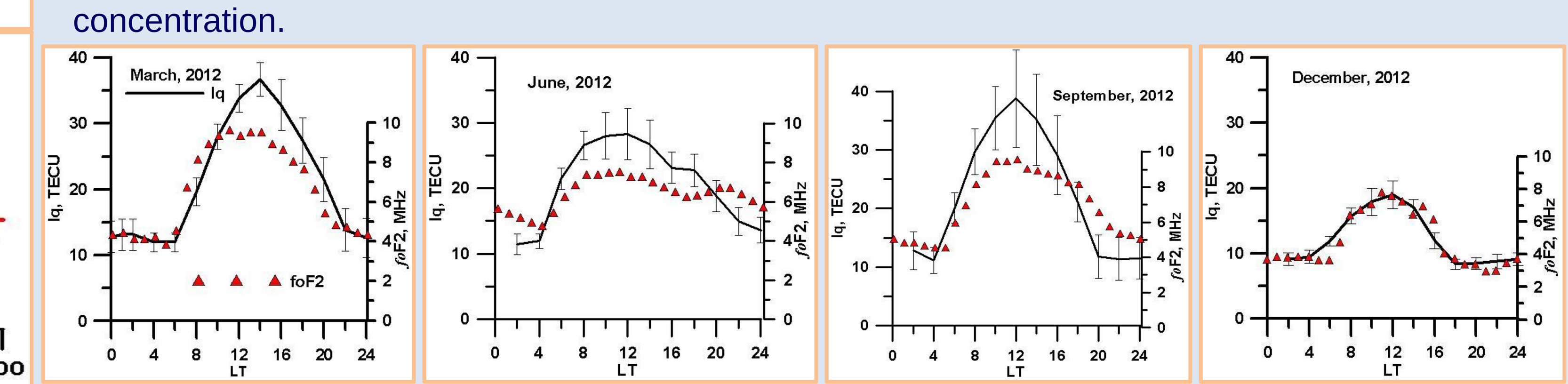
We also studied the diurnal variations of the absolute values of the total electron content during the periods of abnormal low Solar activity (2012), using the GIM maps. The variations of TEC for different seasonal conditions vernal and autumnal equinox and summer and winter solstice were investigated. For each season 10 and more days with most geomagnetic quiet condition with Kp not more than 3, and Dst not less than -50nT were chosen. Data on Dst, Kp were taken from http://www.ngdc.noaa.gov/stp/GEOMAG/ and conditions for region was appreciate by "Alma-Ata" geomagnetic observatory data which is in the part of INTERMAGNET http://geomag.ionos.kz. The diurnal TEC averaged for chosen geomagnetic quiet periods. As a result the average diurnal TEC variations (Iq), characterizing regional behavior of TEC for geomagnetic quiet periods at different season were found. In the figure 4 diurnal TEC variations (*Iq*) calculated for [42.5°N; 75°E] (solid black line) is shown. There by vertical range shown squared average calculated by:

$$\sigma = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (I_i - I_q)}$$

where I_q – TEC averaged for chosen geomagnetic quiet periods, I_i – current TEC.

Maximum of TEC observed at vernal and autumnal equinox midday (35 5) TECU, diurnal variations amplitude for them is about (20 3) TECU. At the conditions of winter solstice the maximal midday TEC is about (20 3) TECU and diurnal variations amplitude for them is about (10 2) TECU. At the conditions of summer solstice the maximal midday TEC is about (25 3) TECU and diurnal variations amplitude for them is about (15 2) TECU. Squared average of current I_i from average I_q maximal in September 2012 г. is about (8 3) TECU, in other mounthes is about (5 3) TECU. Fluctuations of TEC increases at transition from night to day period. So at geomagnetic quiet condition there are exists fluctuations of TEC which increases at transition from night to day periods and this fact should be taken into consideration at searching of ionospheric effects on anthropogenic and natural sources.

F. The TEC behavior compared with diurnal variations of critical frequencies of the F2 layer, f_0F2 according to the data of the radiosond in Almaty [43.38°N; 77.38°E]. Diurnal variations of critical frequencies of the F2 layer, f_0F2 averaged for the same periods as TEC. In diurnal variations of critical frequencies the same peculiarities as in TEC variations observed due to main contribution to TEC is from the region of maximum of ionization of ionosphere. In june like diurnal variations of TEC there are two local maximum at diurnal variations of critical frequencies of the F2 layer, f_0F2 at 11 and 20 LT. These effects are consequences of atmospheric winds system [7]. Pressure gradient of neutral gas at F layer causes intensive atmospheric winds. System of winds induces vertical ionospheric drift which for 09-18 LT directed downward and cause the decreasing of critical frequencies of the F2 layer, f_0F2 in summer. In the evening and nighttime this drift directed upward and causes the increasing of electron concentration.



The vertical curves show the root-mean-square deviations. The red triangles show the diurnal variations of the critical frequency of the F2 ionosphere layer, which were averaged for the same periods, as the TEC variations.

Figure 4 – Averaged for the magnetic calm days 2012 diurnal variations of the total electron content Iq in Almaty, which were calculated with use of GIM-technology

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