Annex 2

Final Report of the Institute of Ionosphere, Almaty, team

1. TITLE, REFERENCE NUMBER

Title: Global structure of gravity waves in the middle and upper atmosphere, their nonlinear coupling, parameterization and impact on atmospheric circulation

Reference number: INTAS 991-1186

Team: Institute of Ionosphere

Leader of the team: Dr. A. Yakovets

2. RESEARCH

2.1 Objectives

According to the working program of the project objectives of this team during the entire term of work under the grant are as follows:

T3. Study of global distribution of activity of large-scale and mesoscale disturbances of ionospheric electron content from the data of LEO GPS satellites and ground-based networks of GPS receivers and dynamical coupling processes in the middle and upper atmosphere;

T4. Validation and comparison of satellite and model data with results of ground-based Lidar and ionosonde observations.

2.2 Research Activities

(1) All participants of the project carried out their activities according to the Work Program given in the INTAS cooperation agreement. A fruitful collaboration with Institute of Solar-Terrestrial Physics, Irkutsk, Russia (Professor E. Afraimovich) and Station of ionospheric and geomagnetic observations, Geophysical survey SB RAS (approached to Institute of Geology and Geophysics, Novosibirsk, Russia) (Dr. S. Khomutov) was performed.

2.3 Scientific Results

During the work the following main results were obtained:

- The technique was developed to determine the spatial parameters of TIDs from the ionosphere-induced phase variations at two carrier frequencies transmitted by low orbital satellites PARUS and CICADA on the basis of known methods of calculating the relative total electron content (TEC) variations. A package of computer codes for statistical analysis of experimental data was developed. These methods are as following: the Blackman-Tukey method for calculating the energy and phase spectra, coherence function being sufficient for estimation of the speed of wave propagation; the method of maximum entropy being able to select spectral peaks with periods comparable the length of time series of experimental data; the method of complex demodulation giving an opportunity to distinguish between coherent wave packets and stochastic fluctuations of the electron content; the bispectral analysis which allows to estimate the degree of non-linear resonant interactions between different spectral components.

- Regular ground-based observations of gravity waves (GWs) are conducted by the Mesopause Oxygen Rotational Temperature Imager (MORTI) measuring the nightglow emission and temperature at altitude of 95 km, the ground-based ionosonde BASIS measuring ionospheric parameters below F layer peak, low orbital (PARUS, CICADA) and high orbital (GPS) satellites. GPS data from more than 800 world wide two-frequency GPS receivers are available through the INTERNET. GPS data for the period analyzed in the project were obtained through INTERNET by using the technique developed by Afraimovich (2000).

- Spectra of AGWs at the mesopause and thermosphere were compared on the basis of nightglow emission and ionospheric (virtual heights of sounding radio signals reflections) observations conducted since October 1997 till February 2001. Two types of virtual height variations (periodical and quasi-stochastic) were found to exist in the thermosphere. The first one is related with AGWs identified by the downward direction of wave phase propagation. The seasonal dependence of AGW presence was found. AGWs were presented during 70-85% of observations conducted in a period since October till March. In the summer, probability of their observations was only 20-40%. The rest part of observations revealed the quasi-stochastic character of virtual height variations. Spectral analysis of simultaneous AGW records for the mesopause and thermosphere revealed a good coincidence of spectral peaks for these atmospheric layers. Two groups of spectral peaks were found in the most spectra both for the mesopause and for thermospheric altitudes. Periods of the first group were ranged in 4.0-8 hours and centered on a period of 6 hours. The rest part of observations revealed that tidal oscillations of the atmospheric layers. The second group including periods of 0.7-4 hours is considered to be a manifestation of AGWs propagation at altitudes considered. Vertical phase velocities of
waves were determined from virtual height variations obtained for different sounding frequencies. The phase velocities were found to increase when the period of a wave decreases.

- An analysis of relations between geomagnetic and TID activities was made on the basis of data of more than a hundred of GPS receivers available via the INTERNET for ten days with different levels of magnetic activity. It was found that power spectra of daytime TEC variations in the range of 20-60 min periods under quiet geomagnetic conditions have a power-law form, with the slope index k≈−2.5. An increase of magnetic activity leads to the increase in integral intensity of TIDs with a concurrent kink of spectra caused by growing electron density variations with periods of 20-60 min. Amplitudes of variations are found to be smaller by night than by day. It was shown that a level of magnetic activity can not be the direct index of TID activity. The largest correlation was observed between the integral power of TIDs and the time derivative of Dst-index of magnetic activity (a maximum coefficient of correlation between those values was found to be of –0.94), the delay between the increase of TID amplitudes and the moment of the maximum time derivative of Dst being of the order of two hours. This fact is consistent with the view that TIDs generated at auroral regions travel equatorward with the average velocities of 200-400 m/s.

- Basic properties of the mid-latitude large-scale traveling ionospheric disturbances (LS TIDs) during the maximum phase of a strong magnetic storm of 6–8 April 2000 are investigated. Total electron content (TEC) variations were studied by using data from GPS receivers located in Russia and Central Asia. The nightglow response to this storm at mesopause and thermospheric altitudes was also measured by optical instruments FENIX located at the observatory of the Institute of Solar-Terrestrial Physics, (51.9° N, 103.0° E) and MORTI located at the observatory of the Institute of Ionosphere (43.2° N, 77.0° E). Variations of the f\textsubscript{F2} and virtual altitudes of the F2 layer were measured at Almaty as well. In the course of the magnetic storm, two types of disturbances were observed. The first one has features of a solitary wave with a period of about 1 hour, and was interpreted as an LS TID originating in the polar latitudes. The second one included short-period variations probably related to the particle precipitation. An analysis of the data has shown that being originated the auroral disturbance induced LS solitary wave with a period of about 1 hour and the front width no less 5000 km traveled equatorward to a distance no less than 1000 km with the average velocity of about 200 m/s. The TEC disturbance, showing mainly a decrease of the electron content in the vicinity of the F2-layer maximum, correlates with an increase of the emission rate in the optical band, with the temporal shift being different for different ionospheric altitudes. At Almaty, the magnetic storm was followed by an extremely large decrease of the electron content in the F2-layer maximum, which caused a decrease of the nighttime critical frequencies by 4-5 MHz. The decrease of the electron content was accompanied by a significant increase of the F2-layer virtual height.

- Simultaneous observations of the ionosphere carried out at distant sites and night airglow at the mesosphere showed that variations of virtual heights of the radio wave reflections from the ionosphere and emission rate may be explained on the basis of presence of low frequency wave components with periods of 4-8 hours identified with harmonics of the tidal wave and high frequency wave components with periods below 4 hours presenting large-scale TIDs. Amplitudes of tidal harmonics change from night to night but very high correlation between these harmonics observed at greatly spaced sites was recorded. Correlation of large-scale TIDs for the same sites was noticeably less.

- The climatology of total electron content (TEC) pulsations based on statistics of 3·105 TEC records obtained from a global GPS network is considered. Two criteria were developed to select pulsations from background variations of TEC. Analysis has shown that only ~ 0.1 % of the total records were characterized as TID pulsations. However, the large absolute figure (~3·10^2) of pulsation events allowed to study their climatology. A comparison number of events with the module of Dst-index of magnetic activity has shown that the probability to observe pulsations are higher for magnetically quiet days compared with disturbed ones. The maximum probability to observe pulsations corresponds to the local noon. In order to estimate an area covered by pulsations, there were computed various distances (dR) between points available where pulsations were presented in the certain temporal interval. It seems that pulsations are localized into space. In spite of a long tail of the distribution extending 2100 km, most of events are restricted by the distance of 500-600km.

- An experimental study of the response of the midlatitude night-time ionosphere F-layer to passing atmospheric gravity waves was carried out. Ionograms were analysed for temporal variations of virtual heights taken for several fixed frequencies reflected in the ionosphere (the virtual heights of the constant electron content), critical frequency of the ionosphere F-layer, and height profiles of electron content (N(h)-profiles). Significant part of observations showed well-defined wave structures on the h'(t) variations observed throughout the entire night, but the corresponding foF(t) variations were less discernible. These h'(t) and foF(t) variations were almost in antiphase. From the h'(t) there is evidence of downward phase propagation of the observed waves. The temporal behaviour of the electron content at series of specific heights allowed obtaining the height profiles of the wave amplitude (eI/m^3). The common shape of the height profiles can be approximated by a parabola with average thickness of ~60 km. No evident seasonal dependence was visible and the dependence on magnetic activity was weak. During magnetic storms there was a tendency for the maximum amplitude, its altitude, and the thickness of the height amplitude profiles to be larger than those under the quiet magnetic conditions.
A consequence of N(h)-profiles calculated for a period of the passing wave showed them to move up and down in phase with the passing wave. As the F-layer is lifted by the positive surge in gravity wave, the electron content at the F-layer peak decreases, the slab thickness being increased also. Subsequently, the opposite happens as h0F falls below its equilibrium value. Such a characteristics of the F layer behaviour is remarkably consistent with results of a model study of the atmospheric and ionospheric response to a short burst of enhanced ion convection at high-latitudes performed with the CTIM model.

Novelty and importance of the results
All of obtained results are new. For the first, time simultaneous observations of atmospheric gravity waves at mesopause and thermosphere showed their similar spectral composition. For the first time, a simultaneous response of the mesopause and thermosphere on a large geomagnetic storm was observed at two spaced sites. For the first time, large correlation was found between integral intensity of total electron density variations and time derivative of Dst-index of geomagnetic activity. For the first time, modeled results of AGW propagation from the auroral region were supported by observations during a magnetic storm.

Studies under the project in one part coincide with the direction of international project PSMOS (Planetary Scale Mesopause Observing System). Participants of the project are working in the PSMOS project.

3. REFERENCES OF PUBLICATIONS FROM THE INTAS PROJECT

1. Published papers:

2. Papers accepted:

3. Abstracts of International Conferences


4. PhD thesis
1. Vodyannikov V.V., Spectral and temporal characteristics of travelling ionospheric disturbances as deduced from ground-based and satellite sounding, Almaty, Kazakhstan, 2002. (Date of defense is March 13, 2002).

2. Aushev V.M., Study of atmospheric waves at the mesopause over the Kazakhstan’s area, Almaty, Kazakhstan, 2002. (Date of defense is March 27, 2002).
Scientific report of the Institute of Ionosphere team

According to the working program of the project the studies in Institute of Ionosphere during the entire term of work under the grant were concentrated around the following scientific tasks:

T3. Study of global distribution of activity of large-scale and mesoscale disturbances of ionospheric electron content from the data of LEO GPS satellites and ground-based networks of GPS receivers and dynamical coupling processes in the middle and upper atmosphere;

T4. Validation and comparison of satellite and model data with results of ground-based Lidar and ionosonde observations.

1. Introduction

Atmospheric gravity waves (AGWs) play an important role in dynamics of the middle and upper atmosphere. AGWs were studied both directly by measuring variations of the neutral atmosphere parameters and indirectly by measuring parameters of travelling ionospheric disturbances (TIDs) being ionospheric manifestations of the neutral gas motion. The main sources of AGW excitation in the atmosphere are considered to be the heating of the polar atmosphere by the auroral electrojet and particle precipitation [Hunsucker, 1982] and topography, frontal and convective activity, and wind shear [Fritts, 1995] at the lower atmosphere as well. AGWs and TIDs were divided into two groups, large-scale and medium- scale ones in accordance with their periods and phase velocities (Georges, 1968). A number of experiments showed that large-scale waves generated in the polar region with the horizontal wavelength of about 1000 km and periods between 30 min and 3 hours propagate equatorward into the thermosphere with the horizontal speeds from 400 m/s to 1000m/s (comparable with speed of the sound in the thermosphere) [Hunsucker, 1982]. Medium-scale waves from the same sources propagate in a duct formed by the Earth’s surface and temperature gradient in the lower thermosphere [Francis, 1973]. A part of energy of medium-scale AGWs leaks through the upper boundary of the duct and induces TIDs. Propagating from the lower to upper atmosphere AGWs transport the large bulk of energy and momentum (AGWs energy per unit mass enlarges by a factor of about 100 from the tropopause to the mesopause [Fritts, 1995]). These fluxes of energy and momentum contribute significantly in dynamics of the mesosphere and thermosphere. Gravity waves are strongly influenced by the tidal winds and wind shear. Intensive theoretical and experimental studies advanced in our knowledge of AGWs and TIDs significantly last decade but their global distribution and spatial structure composing AGWs and TIDs climatology are still not studied sufficiently.

The objectives of these studies are statistical analysis of parameters of atmospheric gravity waves and travelling ionospheric disturbances in the middle and upper atmosphere on the basis of experimental data obtained by optical instruments, GPS satellites, and ground-based ionosondes, also comparison of experimental and modeled results.

According to the project, the following main results have been obtained during the entire term of studies.

2. Comparison of AGW’s spectra near the mesopause and thermosphere

AGWs spectra at the mesopause were obtained from fluctuations of the O_2 atmospheric (0-1) night airglow measured by the MORTI (Mesopause Oxygen Rotational Temperature Imager) instrument installed near Almaty at altitude of 2500m. AGWs spectra in the thermosphere were studied from fluctuations of virtual heights at series of sounding frequencies reflected from the F2 layer of the ionosphere. Night observations of TIDs in the F region of the ionosphere were carried out since October 1997 till present time by digital multi-functional ionosonde BASIS installed at Institute of Ionosphere. The ionograms were analyzed for virtual heights ($h'(t)$), critical frequency ($f_0F2(t)$), and $N(h)$-profiles. $h'(t)$ at series of operating frequencies were selected to study TIDs spectra.

The same techniques were used for processing optical and ionospheric data. In order to remove trend from original time series they were smoothed by the quadratic polynomial. In order to resolve low-frequency spectral components whose periods are comparable to the record length, the technique of maximum entropy power spectral analysis was used to examine the spectral properties of time series recorded.

During the period since 1997 till 2001 years 231 series of ionospheric and 300 series of optical observations were performed. All ionospheric series were divided to form two groups. The first group comprises series with quasi-periodic variations. Figure 1a presents a typical example such kind of variations of virtual heights ($h'(t)$) at series of specific frequencies. The second group comprises quasi- stochastic variations. Figure 1b presents a typical example such kind of variations of virtual heights ($h'(t)$) at series of specific frequencies obtained at neighboring night. Table 1 presents distributions different types of variations for different months.

Table 1. Distribution a number of series of observations characterized as quasi- periodic and –stochastic variations

<table>
<thead>
<tr>
<th>Month</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
<th>XI</th>
<th>XII</th>
<th>Σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>11</td>
<td>22</td>
<td>16</td>
<td>15</td>
<td>15</td>
<td>24</td>
<td>21</td>
<td>23</td>
<td>231</td>
</tr>
</tbody>
</table>
It is seen from the table that the total number of series characterized with quasi-periodic variations of $h'(t)$ is about 70%. Also it is seen that the most favorable seasons for observations TIDs are autumn and winter including the beginning of spring. In the summer a probability to observe TIDs is noticeable less.

Figure 2 presents variations of nightglow emission and $\Delta h'(t)$ for a number of observations. It is clear that there is good correlation between long period components of these variations. In order to compare the nightglow emission and $\Delta h'(t)$ variations of all spectral components a method of maximum entropy was applied and its results are presented in table 2.

Table 2. Results of spectral analysis of ionospheric and optical series for various nights of observations

<table>
<thead>
<tr>
<th>Date</th>
<th>Time, UT (hour)</th>
<th>$f_1/ f_2$ (MHz)</th>
<th>Period, (hour)</th>
<th>Time, UT (hour)</th>
<th>Period, (hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997/10/30</td>
<td>15.01-01.01</td>
<td>2.5, 3.5</td>
<td>4.2, 0.6</td>
<td>12:44-00:33</td>
<td>5.0, 2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.3, 1.3</td>
<td></td>
<td>5.6, 2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5, 0.7</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>1998/02/02</td>
<td>16.34-01.51</td>
<td>2.5, 4.0</td>
<td>5.3, 0.6</td>
<td>16.42-01.03</td>
<td>2.3, 1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.7, 1.2</td>
<td></td>
<td>1.1, 0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td></td>
<td>1.1, 0.7</td>
</tr>
<tr>
<td>1998/02/24</td>
<td>13.93-01.01</td>
<td>2.5, 3.5</td>
<td>6.0, 2.2</td>
<td>13.5-00.5</td>
<td>2.8, 1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.2, 1.9</td>
<td></td>
<td>5.6, 1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.0, 0.8</td>
<td></td>
<td>1.3, 0.9</td>
</tr>
<tr>
<td>1999/02/18</td>
<td>13.01-01.51</td>
<td>2.5, 3.5</td>
<td>8.4, 2.8</td>
<td>13.30-00.35</td>
<td>6.4, 1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.1, 2.3</td>
<td></td>
<td>2.8, 1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.3, 1.5</td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>
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In Table 2 periods of spectral peaks are presented. Spectra of the \( h'(t) \) variations are calculated for two specific sounding frequencies \( (f_1, f_2) \). The upper line in spectra of optical observations corresponds to spectral peaks of a temperature variation spectrum and lower line in spectra of optical observations corresponds to spectral peaks of an emission variation spectrum.

It is seen that both ionospheric and optical observations reveal low frequency components with periods in a band of 4-8 hours which are identified with tidal harmonics \( (n=3-6) \). Waves with periods less than 4 hours are identified with AGWs.

From the Table it is also seen that values of periods of spectral peaks for specific frequencies do not always coincide. This frequency shift was also observed by Shibata and Schlegel (1993) and explained on the basis of Doppler’s shift caused by a height gradient of horizontal velocity of the background wind.

Some differences between periods of spectral peaks of ionospheric and optical variations seem to be explained in terms of Doppler’s effect as well. Some differences between periods of spectral peaks of temperature and emission variations seem to be induced by a high level of noise in temperature records.

The \( h'(t) \) records obtained for a number of different altitudes allow to define vertical velocities of wave phase fronts for various spectral components. Table 3 comprises the velocities for three dominating frequency components averaged over 12 nights of observations carried out in October-December 2000.

The table shows that wave vertical velocity grows when a wave period decreases.

Table 3. Averaged vertical phase velocities for three dominating wave periods

<table>
<thead>
<tr>
<th>Period, hour</th>
<th>6</th>
<th>2.5</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity, m/sec</td>
<td>12.4</td>
<td>21.1</td>
<td>41.7</td>
</tr>
</tbody>
</table>

3. Geomagnetic control of the spectrum of traveling ionospheric disturbances
The main characteristics of wave processes are the temporal and spatial spectra of TIDs. Since the spectra normally have a power-law character, the slope of the spectrum \( k \) and the standard deviation of intensity variations in the frequency range \( M \) (the amplitude scale of the power spectrum) are the most informative parameters. Estimates of these parameters were made in almost all of the publications of an experimental or theoretical nature. Determining the above-mentioned characteristics of disturbances experimentally is of crucial importance for validating the interpretation of experimental data in terms of different physical mechanisms of the inhomogeneous structure. Furthermore, a knowledge of irregularity spectra is required for developing an empirical model of distortions of transionospheric signals used in special purpose radio engineering systems of communication, location, and navigation in the meter, decimeter and centimeter ranges.

Published data show a large scatter in estimates of the slope \( k \) and of the amplitude scale \( M \) of temporal and spatial spectra. One of the reasons for this scatter might be that different measuring techniques are used, which differ greatly in spatial and temporal resolution. However, the main reason is determined by the differing geophysical conditions of separate measurements, and by the large difference in latitude, longitude and local time when carrying out experiments. More reliable information requires carrying out simultaneous measurements over a large area covering regions with a different local time. A network of 900 GPS receivers distributed all over the world meets such requirements. High precision measurements of the group and phase delay along the line of sight (LOS) between the receiver on the ground and the transmitters on the GPS satellites supply with temporal behavior of total electron content (TEC).

This study is based on using the data from the global GPS network of receiving stations available via the Internet. The set of stations selected from the part of the global GPS network available to us covers rather densely both North America and Europe, and much less so, Asia.

**Table 4. General information about experiment**

<table>
<thead>
<tr>
<th>N</th>
<th>Data</th>
<th>Day</th>
<th>m</th>
<th>( Dst_{\text{min}} ), nT</th>
<th>( Kp_{\text{max}} )</th>
<th>( I_{\text{max}} ), UT</th>
<th>( M_{\text{max}} ), TECU</th>
<th>( \tau ), hour</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26/27 Aug 1998</td>
<td>238/239</td>
<td>93/88</td>
<td>-188</td>
<td>8</td>
<td>0.32</td>
<td>2</td>
<td>-0.937</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>24/25 Sep 1998</td>
<td>267/268</td>
<td>96/87</td>
<td>-233</td>
<td>9</td>
<td>0.42</td>
<td>2</td>
<td>-0.840</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>29 Jul 1999</td>
<td>210</td>
<td>161</td>
<td>-40</td>
<td>3</td>
<td>0.16</td>
<td>2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>9 Jan 2000</td>
<td>009</td>
<td>332</td>
<td>-13</td>
<td>-</td>
<td>0.21</td>
<td>2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6/7 Apr 2000</td>
<td>097/098</td>
<td>179/180</td>
<td>-321</td>
<td>8</td>
<td>1.07</td>
<td>2</td>
<td>-0.848</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>15/16 Jul 2000</td>
<td>197/198</td>
<td>309/308</td>
<td>-295</td>
<td>9</td>
<td>0.67</td>
<td>2</td>
<td>-0.846</td>
<td></td>
</tr>
</tbody>
</table>

We carried out an analysis of the data for a set of 300 GPS stations for 10 days from the time interval 1998–2000, with a different level of geomagnetic disturbance \( (Dst \text{ from } -13 \text{ to } -321 \text{ nT}; Kp\text{-index } \text{from } 3 \text{ to } 9) \). Table 4 presents information about day numbers, the number of the stations used, \( m \), and extreme values of \( Dst_{\text{min}} \) and \( Kp_{\text{max}} \). A total amount of the GPS data exceeds \( 5 \times 10^3 \) 30-s observations.

The method implies using an appropriate processing of TEC variations that are determined from the GPS data, simultaneously for the entire set of GPS satellites (as many as 5–10 satellites) “visible” during a given time interval at all stations in the GPS network used in the analysis.

The standard GPS technology provides a means for wave disturbance detection based on phase measurements of TEC at each of the spaced two-frequency GPS receivers. A method of reconstructing TEC variations from measurements of the ionosphere-induced additional increment of the group and phase delay of the satellite radio signal was detailed and validated in a series of publications.

A calculation of a single spectrum of TEC variations involves using a continuous series of \( \text{Io}(t) \) a duration of no less than 2.5 hours. To exclude the variations in the regular ionosphere, as well as trends introduced by the motion of the satellite, we employ the procedure of removing the linear trend by preliminarily smoothing the initial series with a selected time window with duration of about 60 min.

The logarithmic power spectrum \( \lg S^2(F) \) of detrended series of TEC is calculated by using a standard FFT procedure. Incoherent summation of the partial power spectra \( \lg S^2(F) \), of different LOS was performed by the formula

\[
\langle \lg S^2(F) \rangle = \frac{1}{n} \sum_{i=1}^{n} \lg S^2(F)_i
\]

where \( i \) is the number of LOS; \( i = 1, 2, \ldots \ n \).

An example of estimating parameters of TID spectra Figure 3 presents temporal behavior of the “oblique” TEC \( I(t) \) of the magnetically disturbed day of 15 July 2000 for the time interval 17:00-19:00 UT, preceding the onset of a geomagnetic disturbance over the Millstone Hill incoherent station within the rectangle 30 – 50° N, 270 – 290° E (a), and \( dl(t) \) variations filtered from the \( I(t) \) series by removing the trend with a 60-min window for station WES2 (PRN17) (b) logarithmic power spectrum \( \lg S^2(F) \) of the \( dl(t) \) series presented in panel (c); average (for 16 beams of 10 GPS stations located inside this territory) logarithmic power spectrum \( \langle \lg S^2(F) \rangle \) (d). The same as above, but for the onset of a geomagnetic disturbance over this territory for the time interval 20:00-22:00 UT, and for station ALGO (PRN21) (e – h) average (for 7 beams) logarithmic power spectrum \( \langle \lg S^2(F) \rangle \). For the purpose of comparing the spectra for the quiet and disturbed days, in panels (d) and (h) a thin line shows the spectrum for the quiet day of 29 July 1999 obtained by...
averaging over \( n = 309 \) beams of 161 global network stations. Boldface letters and dots along the abscissa axis in panels (e, d, g) and (h) show the frequency ranges of medium-scale (MS) and small-scale (SS) irregularities.

As is evident from Fig. 3d, the spectrum of a quiet day corresponds reasonably well to a theoretical power spectrum of ionospheric irregularities with a slope of about \( k = -2.5 \) (Francis, 1974), and it can therefore be used as a reference power spectrum. In this case, the TEC fluctuation scale \( M \) in the MS range and \( C \) in the SS range does not exceed the values 0.4 and 0.007 TECU, respectively.

When comparing the average spectra of TEC variations from 15 July 2000 for the time interval 17:00-19:00 UT with the spectrum from the quiet day of 29 July 1999, one can notice an order of magnitude excess of the TEC disturbance level throughout the spectrum with the value of the slope \( k = -2.56 \) remaining the same. However, there is also a clear disproportionate (by a 1.5 order of magnitude) increase in TEC variation intensity in the MS range.

Still more drastic changes in the ionospheric irregularity spectrum occurred over the same region just one hour later. Figure 3e presents the time dependence of the disturbed value of the “vertical” TEC I \( t \) (for station ALGO (satellite number PRN21) for 15 July 2000, for the time interval 20:00–22:30 UT. For the same series, Fig. 3f plots the \( d I / dt \) variations that were filtered out from the I \( t \) series by removing the trend with a 60-min window. As is apparent from Fig. 3a, and from the corresponding \( \lg S^2(F) \) spectrum, Fig. 3g, the TEC variations increased in power at a minimum by two orders of magnitude against the time interval 17:00-19:00 UT (Figs. 3b and 3c). In addition, there was an abrupt change in the spectrum slope \( k = -0.85 \), which is indicative of a disproportionate increase in irregularity intensity in the MS and SS parts of the spectrum. In this case, the TEC fluctuation scale \( M \) in the MS range and \( C \) in the SS range exceeds in the values 4.27 and 0.5 TECU, respectively.

The result derived from combining the \( \lg S^2(F) \) spectra for 7 LOS is shown in Fig. 3h by a thick line. The spectrum has a power-law character, yet the mean slope of \( k = -1.85 \) differs markedly from the value of \( k \) for the magnetically quiet day. The mean intensity \( M \) of the irregularities of the medium-scale part increased by two orders of magnitude, and the intensity of the small-scale part increased immediately by three orders of magnitude as compared with the level of the magnetically quiet day.

Comparison of temporal behavior of \( M(t) \) in the range of 20–60 min periods with \( Dst(t) \) index of magnetic activity showed that an increase in the level of magnetic activity is accompanied by a gradual increase in the total intensity of TIDs; however, it correlates not with the absolute level of \( Dst \), but with the value of the time derivative \( d(Dst)/dt \) (a maximum correlation coefficient reaches 0.94). The delay \( \tau \) (of about 2 hours) in the increase of TEC intensity with respect to rapid changes in magnetic field strength is easy to explain by taking into consideration that the greatest contribution in a global averaging of TID spectra is made by the mid-latitude chain of GPS stations. This chain of GPS stations is about 2000 km from the southern boundary of the auroral source of TIDs which is produced during geomagnetic disturbances. TIDs that are generated once this source is produced travel equatorward with the velocity of the order of 300–400 m/s.

For studying the diurnal dependence of TID spectrum characteristics, we carried out an averaging of the spectra with due regard for the local time LT for each GPS station. According to analysis performed, the power spectra of the daytime TEC variations in the range of 20–60 min periods under quiet conditions have a power-law form with the slope index \( k = -2.5 \) which remains virtually unchanged over the course of that day. With the increasing level of geomagnetic disturbance, there is an increase in the total intensity of TIDs, with a concurrent kink of the spectrum caused by an increase in fluctuation intensity in the range of 20–60 min. The TEC variation amplitude is smaller at night than during the daytime, and the spectrum decreases in slope, which is indicative of a disproportionate growth of the amplitude of the small-scale part of the spectrum.

Our findings bear witness to the determining role of geomagnetic disturbances in the formation of the spectrum of traveling ionospheric disturbances. This conclusion is based on substantially more extensive (than obtained earlier) statistical material. It spans periods with a different level of geomagnetic disturbance, and has a global character. The analysis has been made for a set of 100 to 300 GPS stations for 10 days with a different level of geomagnetic activity \( (\text{Dst} \text{ index from 3 to 9}) \). It was found that power spectra of daytime TEC variations in the range of 20–60 min periods under quiet conditions have a power-law form with the slope index \( k = -2.5 \). With an increase in the level of magnetic disturbance, there is an increase in the total intensity of TIDs, with a concurrent kink of the spectrum caused by an increase in oscillation intensity in the range of 20–60 min. The TEC variation amplitude is found to be smaller at night than during the daytime, and the spectrum decreases in slope, which is indicative of a disproportionate increase in the amplitude of the small–scale part of the spectrum. It was found that an increase in the level of geomagnetic activity is accompanied by an increase in the total intensity of TEC; however, it does not correlate with the absolute level of \( Dst \), but rather with the value of the time derivative of \( Dst \) (a maximum correlation coefficient reaches −0.94). The delay in the TID response of the order of 2 hours is consistent with the view that TIDs are generated in auroral regions, and propagate equatorward with the velocity of about 300–400 m/s.

4. Response of the mesosphere and thermosphere to a large magnetic storm

In the course of strong geomagnetic storms, significant changes in main structural elements of the magnetosphere and ionosphere occur. Geophysical manifestations of extremely strong magnetic storms are of particular interest because these storms take place relatively rarely (no more than 4 events during an 11-year solar cycle), and therefore the representative statistics of the whole complex of interactive processes in the “magnetosphere- ionosphere” system is lacking. Large-scale traveling ionospheric disturbances (LS TIDs) with a period of 1–2 hours and a wavelength...
of 1000–2000 km constitute the most significant mid-latitude consequence of magnetic storms. Many papers including review papers (Hunsucker, 1982; Hocke and Schlegel, 1996) have been published. LS TIDs are considered to be a manifestation of internal atmospheric gravity waves (AGWs) excited by sources in the polar regions of the northern and southern hemispheres. Thus, the study of LS TIDs provides important information on auroral processes under quiet and disturbed geomagnetic conditions.

The objective of this section is to study the response of the mid-latitude ionosphere to the strong magnetic storm of 6 April 2000 by using data of simultaneous radio and optical observations in Russia and Central Asia, main attention being paid to LS TIDs with a characteristic temporal period of the order of 1 hour. To determine parameters of TIDs in the upper ionosphere the GPS technique is used. Parameters of disturbances at altitudes of the mesopause are defined by the Mesopause Rotational temperature Imager (MORTI) instrument installed near Almaty in mountains at 2800 m above sea level. An optical facility FENIX settled at Geophysical observatory attached to Institute of Solar-Terrestrial physics SD RAS at 100 km from Irkutsk city (51.9° N, 103.0° E; geomagnetic latitude is 41.0° N, L=2) was also applied at observations. It includes a four-channel zenith photometer and a high sensitive TV-system comprising an electron – optical amplifier and a CCD (charge coupled device) array. Following observations of nightglow emissions were made: the OI (557.7 nm) emission which originates from a layer centered at 97 km and with boundaries at altitudes of 85–90 km and with boundaries at altitudes of 75–115 km, the OI (630.0 nm) emission which originates from a layer centered at 250–270 km and with boundaries at altitudes of 160–300 km, the O2 (360–410 nm) emission which originates from a layer centered at 97 km, and the OH emission which originates from a layer centered at 85–90 km and with boundaries at altitudes of 75–115 km.

GPS receiver array used for observations comprises only 11 stations whose coordinates are listed in Table 5. Parameters of LS TIDs are considered to have been determined with a proper reliability when the distances between GPS receivers exceed the wavelength of TIDs (about 1000 km). The array of GPS receivers used in the experiment satisfied this requirement.

Table 5. GPS sites and optical instrument names and locations

<table>
<thead>
<tr>
<th>No</th>
<th>Instrument</th>
<th>Latitude ° N</th>
<th>Longitude ° E</th>
<th>tmin, UT</th>
<th>Amax, TECU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>129.68</td>
<td>18.38</td>
<td>-4.55</td>
</tr>
<tr>
<td>2</td>
<td>ARTU</td>
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<td>58.56</td>
<td>19.00</td>
<td>-4.94</td>
</tr>
<tr>
<td>3</td>
<td>KSTU</td>
<td>55.99</td>
<td>92.79</td>
<td>19.00</td>
<td>-3.78</td>
</tr>
<tr>
<td>4</td>
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<td>55.69</td>
<td>36.76</td>
<td>19.02</td>
<td>-0.95</td>
</tr>
<tr>
<td>5</td>
<td>IRKT</td>
<td>52.22</td>
<td>104.32</td>
<td>19.68</td>
<td>-2.28</td>
</tr>
<tr>
<td>6</td>
<td>URUM</td>
<td>43.80</td>
<td>87.60</td>
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</tr>
<tr>
<td>7</td>
<td>SELE</td>
<td>43.18</td>
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<td>-0.71</td>
</tr>
<tr>
<td>8</td>
<td>SHAS</td>
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<td>75/31</td>
<td>20/92</td>
<td>-0.69</td>
</tr>
<tr>
<td>9</td>
<td>KUMT</td>
<td>41.86</td>
<td>78/19</td>
<td>20/99</td>
<td>-0.91</td>
</tr>
<tr>
<td>10</td>
<td>TRAB</td>
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<td>39.77</td>
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<tr>
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<td>66.88</td>
<td>21.04</td>
<td>-0.61</td>
</tr>
<tr>
<td>12</td>
<td>FENIX</td>
<td>52.9</td>
<td>103.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>MORTI</td>
<td>43.05</td>
<td>76.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4 and Fig. 5 show the initial l(t) and detrended time-series dl(t). For the YAKZ site, only data from the PRN30 satellite for the interval 17.00 – 20.00 UT were available for technical reasons. Almost all GPS records show a gradual decrease of l(t) till a certain time (tmin) corresponding to minima (designated by diamonds in Fig. 4 and 5) in TEC variations, tmin depending on the latitude of the GPS site. Large fast variations of TEC occur for some sites after tmin has elapsed.

Satellite PRN25 was chosen for all GPS sites analyzed (except YAKZ) because its minimum elevation angle θ(t) exceeded 45° for every station during 19.00 – 21.00 UT. Thus, the error of converting the slanting TEC to vertical one caused by the difference between the actual and spherically-symmetric spatial TEC distributions was minimized.

The values of tmin corresponding to minimum TEC (Fig.4, 5) and amplitudes (Amin) expressed in TECU are listed in Table 5. As it is seen, a minimum dl was first recorded for the subionospheric point of station YAKZ at 57° N latitude (thin line in Fig.4c), and, after that, almost simultaneously it was recorded near 53° N latitude at stations ZWEN, ARTU, KSTU (Fig.4 a, d; b; e; c, f respectively) which are extended along the same parallel over the longitudinal difference of 47°. Clearly, the ionospheric disturbance had a wave front with its length exceeding 5000 km. Forty minutes later this disturbance was recorded at the subionospheric point for station IRKT at 51.5° N latitude (Fig.5a, d). Two hours later a similar disturbance dl(t) was recorded at a chain of stations TRAB, SELE (Fig. 5 b, e), KITS, KUMT and URUM (Fig. 5 c, f) at 40° – 45° N latitudes.

By using Table 5 and Fig. 4 and 5, one can study the evolution of the disturbance as it travels equatorward. The amplitude (Amin) of the disturbance dl(t) decreases from 5 TECU at the northern chain of stations to 1 TECU at the southern chain. Moreover, large fast variations dl(t) typical of the high-latitude ionosphere were recorded after passing a minimum dl(t) at the northern chain of stations. The same result was obtained by Afraimovich et al. (2000). These variations are noticeably less at the southern chain of stations.
These features of the $dl(t)$ variations seem to be accounted for the fact that at about 19.00 UT satellite-receiver lines for the northern chain of stations crossed the southern boundary of the auroral zone moving southward. If the front of the disturbance has traveled with a constant velocity, then a delay on the order of 2 hours between the times of the rise of the disturbances at the northern and southern chains of stations corresponds to the southward velocity of about 200 m/sec.

So, in the main phase of the strong magnetic storm, a significant descent on the order of 15–20 TECU was observed at the northern chain of GPS sites, including ZWEN, ARTU, KSTU and YAKZ. Hunsucker (1982) and Balhazor and Moffett (1999) showed that a large area of the polar atmosphere leaving abruptly the state of equilibrium must become the source of LS TIDs traveling equatorward.

Variations of the nightglow emission rate, derived from the zenith photometer observations on 6 April 2000, are plotted in Fig.6a. The main feature of these variations is a significant increase of the OI (630.0 nm) emission in the second half of the night (Fig.6a, line 1) by a factor of 20 compared with values observed near midnight and the last geomagnetic quiet night of 5 April 2000 (Fig.6a, line 3). It can be seen that the OI (630.0 nm) emission grew after 16.00 UT till sunrise when the observations were completed, and periodical variations were superimposed on the gradual growth. The OI (557.7) emission variations (Fig.6a, line 2) revealed a small disturbance near 17.00 UT coinciding with a similar disturbance in the OI (630.0 nm) emission, and an abrupt rise (35%) coinciding with the first phase of the OI (630.0 nm) emission rate maximum increase.

A gradual increase of $O_2$ (360–410 nm) emission, not typical of the quiet geomagnetic state (Fig.6b, line 6 for the previous night of 5 April 2000) (Fig.6b, line 4) was observed with superimposed irregular short-period variations, to begin at 17.00 UT. The $720–830$ nm emission (Fig.6b, line 5) revealed a gradual decrease from 14.00 till 16.00 UT and at ended 16.00 UT when the commencement of the geomagnetic storm occurred.

It is of interest to compare these data with variations of TEC measured at the nearest GPS station IRKT. Records of the 630 nm and 577.7 nm emission lines ($A(t)$) and ($B(t)$) filtered out from the initial data (Fig.6a, lines 1 and 2 respectively) as it was done with TEC $R(t)$, are plotted in Fig.5d. It is seen that there is a good correlation between these variations, and the emission variations are in an opposite phase compared with TEC variations.

Observed at Almaty filtered variations of the $O_2$ (867.6 nm) emission are plotted in Fig.5e together with variations of TEC $R(t)$ for the GPS station SELE. It is seen from Fig.5e that there is a good correlation between the variations of the GPS and MORTI data. By comparing Fig.5d and Fig.5e, it becomes evident that the phase delays between the variations of the GPS and optical data are different for Irkutsk and Almaty. This difference is explicable by the different altitudes of the nightglow emissions, and the different types of optical instruments.

5. Wave activity observed at spaced sites of the ionosphere and mesosphere

Measurements described at section 4 showed that the large-scale TIDs generated by sources located in the aurora region traveled at significant distances practically without changing their form. At the same time the middle-scale TIDs revealed the fast spatial decrease of their similarity. Velthoven et al. [1990] has shown that a length of the spatial coherence at the east-west direction was about 200 km. Crowley and McCrea [1988] found the coherence length of the order of 100 km. Extended studies of the coherence in vertical and horizontal planes were carried out by Yakovets et al. [1995]. The coherence length was found to be dependent of a period of TIDs. It decreased when the period of TIDs decreased. For TID periods exceeding 1 hour the coherence length obtained during observations which were carried out by night was significantly larger than that obtained during daytime. Yakovets et al. [1995] estimated the coherence length in the horizontal plane for the night TIDs by extrapolating an experimental dependence of the coherence value versus a distance. Because the coherence length was estimated to be of the order of 750 km but the experimental dependence were measured in the limit of 60 km it is obvious that a large error could be expected as a result of an extrapolation.

Besides, a length of experimental time-series of 6 hours did not allow obtaining a good spectral resolution for the low frequency TIDs. Thus, the objectives of studies within this section the comparative analysis of wave signatures measured at two sites 1400 km apart and two atmospheric layers (the mesosphere and thermosphere) and an estimate of a value of the longest periods of night wave-like variations of the ionospheric plasma and mesopause airglow emission. Night observations of TIDs in the F region of the ionosphere are carried out by an digital ionosondes BASIS set at Almaty (76°55'E, 43°15' N) and PARUS set at Novosibirsk (83°12' E, 54°36' N). Mesopause Oxygen Rotational Temperature Imager (MORTI) was used for emission rate / temperature measurements giving an information on AGWs parameters at altitude of 95 km.

Figure 7 shows examples of detrended variations ($\Delta h'(t)$) of virtual heights of F-layer for the frequency of 2.5 MHz at Novosibirsk (thin lines) and Almaty (thick line) for 4 nights in November, 2000. Local standard time of Novosibirsk and Almaty is obtained by adding 5 hours to the universal time (UT). All plots reveal features being common for every series of observations. All time-series are dominated by the high-amplitude low-frequency component with a period ranging in the band of 4–8 hours. Amplitude of this component changes from the observation to observation, a mode of the change being the same at Novosibirsk and Almaty. The phase regularity of these 4-8 - hours oscillations can be seen as well. The first wave crest is located in the vicinity of 16.00 UT. The position of the second one is close to 22.00-24.00 UT. Besides, all time-series comprise high-frequency components with periods less than ~ 4 hours. Visual inspection of time-series for spaced stations indicates that their signatures reveal a good resemblance. In order to estimate the degree of resemblance between data obtained at different specific frequencies at the certain site and that between data obtained at spaced sites at the certain specific frequency cross-correlation analysis was applied. Cross-correlation
functions were calculated separately for high- and low-frequency components of time-series. To select these components the high- and low-pass filtration of raw data was made by using the running average with a window length of 2 hours. There are good correlation between raw data of spaced sites and noticeably higher correlation of low frequency components even for such a large distance between observational sites. High frequency components revealed not so good correlation. Table 6 contents values of the $R_{xy}(k)$ maximums for all time-series available simultaneously for both sites.

Besides, the table comprises shifts of the $R_{xy}(k)$ maximum relatively to the phase delay of Almaty variations relatively Novosibirsk ones. From the Table 6 one can see that low frequency components are characterized with large values of $R_{xy}(k)$ maximums except a night of December 24, 2000. Note that this night is characterized with the lowest amplitude of variations. Spectral analysis of raw data has shown that low frequency components had periods ranging in the band of 4-8 hours. High frequency components showed lower correlation. However, for three nights (22.11.2000, 30.11.2000, 20.01.2001) correlation of the high frequency components was large enough to estimate with the good confidence a speed of the wave front propagation between Novosibirsk and Almaty. These speeds were 460 m/sec, 180 m/sec, and 425 m/sec. Comparing values of horizontal and vertical speeds one can conclude that the phase front of these component is strongly tilted to the horizon.

In light of the above, it becomes imperative to compare temporal variations of virtual heights of F-layer and variations of $O_2$ emission rate at the mesopause altitude. Figure 2 shows detrended variations ($\Delta h'(t)$) of virtual heights of F-layer at different specific frequencies (thick line) and variations of $O_2$ emission rate at the mesopause altitude (thin line) for 8 nights. Such as in Figure 7 all time-series are dominated by the high-amplitude low-frequency components which reveal a good resemblance between ionospheric and optical signatures. In order to estimate the degree of resemblance between data cross-correlation analysis was applied. Cross-correlation functions were calculated separately for high- and low-frequency components of time-series. To select these components the high- and low-pass filtration of raw data was made by using the running average with a window length of 2 hours. Table 7 contents values of the $R_{xy}(k)$ maximums for several series presented in Figure 7.

Table 6.

<table>
<thead>
<tr>
<th>Date</th>
<th>Novosibirsk – Alma-Ata ( $h_{1N} – h_{1A}$ )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-pass filter</td>
</tr>
<tr>
<td></td>
<td>$R_{xy}$</td>
</tr>
<tr>
<td>22.11.2000</td>
<td>0.9514</td>
</tr>
<tr>
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</tr>
<tr>
<td>28.11.2000</td>
<td>0.9293</td>
</tr>
<tr>
<td>30.11.2000</td>
<td>0.9937</td>
</tr>
<tr>
<td>24.12.2000</td>
<td>0.5765</td>
</tr>
<tr>
<td>25.12.2000</td>
<td>0.9411</td>
</tr>
<tr>
<td>20.01.2001</td>
<td>0.9718</td>
</tr>
<tr>
<td>23.01.2001</td>
<td>0.8767</td>
</tr>
</tbody>
</table>

The sources of the low frequency variations that reveal good correlation even between distant sites of observations may have a different origin. Periods of the large scale TIDs are assumed to be restricted by a value of 3 hours [Hunsucker, 1982]. Hence, according to the accepted definition, variations with periods ranging from 4 to 8 hours could not be classified as TIDs. Calculation of vertical phase velocities for these components both at Novosibirsk and Almaty showed that their phase front progressed downward demonstrating features being common with TIDs ones. From Table 6 one can see that the phase of low frequency components at Novosibirsk equals or slightly leads that at Almaty.

Table 7.

<table>
<thead>
<tr>
<th>Date</th>
<th>$\Delta h'(t) – E(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-pass filter</td>
</tr>
<tr>
<td></td>
<td>$R_{xy}$</td>
</tr>
<tr>
<td>30.10.97</td>
<td>0.89</td>
</tr>
<tr>
<td>2.02.98</td>
<td>0.86</td>
</tr>
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<td>27.02.98</td>
<td>0.96</td>
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<td>0.81</td>
</tr>
<tr>
<td>18.02.99</td>
<td>0.94</td>
</tr>
</tbody>
</table>
proving their westward migration. Besides, as it is clear from Figure 7 the phase of the low frequency component is linked with a local time. These facts make the basis to conclude that the low frequency components may be the harmonics of the tidal wave.

Let us consider others possible sources of low-frequency components in the spectrum of variations observed. The diurnal variation of $h'F$ is characterized by the day-time minimum and night-time maximum. In addition to the main $h'F$ maximum around the midnight, the second peak in $h'F$ occurs in the morning hours, before the sunrise at the F-region altitudes. This peak is preceded by a well-defined minimum. The great bulk of experimental data show that the second maximum is most pronounced for lower latitude stations, and becomes practically unobservable at latitude of the order of $45°$ (Hajkowicz, 1991). A sequence of the midnight and morning maxima separated by a minimum can potentially create an apparent picture of the night ionospheric wave-like variations. At least, two alternative mechanisms are considered to be a reason of the morning height rises in the $h'F$. According the first one (Rishbeth et al., 1995), the ion production beginning initially at very high altitudes in sunrise causes a temporary upward jump of $h'F$ as the new F-layer appears upper the residual night-time F-layer. After that $h'F$ decreases fast as the height of maximum of ion production drops towards its daytime level in F1-layer. This mechanism is not supported by our experimental data showing presence of low-frequency variations of neutral atmospheric constituents at the mesopause altitude. According the second one (Hajkowicz, 1991), the occurrence of this morning peak close to the sunrise at the F-region might indicate that it is generated by the supersonic motion of the sunrise terminator between latitudes $±45°$. Hajkowicz (1991) has obtained his results on the Japanese chain of ionospheric stations. If his results are valid for other geographical regions, the peak in $h'F$ generated by the supersonic motion of the sunrise terminator should not be expected in the morning hours before the sunrise at the F-region altitudes for Almaty and especially Novosibirsk which latitudes exceed $45°$.

Recent observations (Hocke, 1996) of ionospheric parameters performed with the EISCAT radar showed that the first six tidal harmonics were present without noticeable power differences between 100 and 200 km. At heights from 200 to 300 km, diurnal, semi-diurnal, and terdiurnal tidal variations become dominant. These heights coincide with the range covered by specific frequencies used in our experiment. The first and second harmonics we could not find because of polynomial filtration of row data but 3-d and 4-th harmonics dominated in our data. Hocke, (1996) analyzed heights profiles of tidal amplitude and phase as well. The phase (local time of maximum amplitude) for terdiurnal tidal variations at 250 km was found to be equal to $4\ h$our (LT). As it can be seen from Figure 7 the phase of dominant variations is close to this meaning. Thus, our results are consistent well with the results of the EISCAT measurements and it serves as strong support the fact that long-period variations of $h(t)$ and $E(t)$ are the tidal harmonics.

6. The climatology of TEC pulsations based on data from the GPS network

Sometimes experimental studies of TIDs carried out by measuring Doppler frequency shifts in ionospherically reflected radio waves reveal packets of quasi-monochromatic variations of the F-layer electron content. This variations were accompanied with pulsations of magnetic field measured on the ground (Rishbeth and Garriot, 1964, Poole and Sutcliffe, 1987). Based on the electric and magnetic pulsation fields for partially reflected downcoming Alven wave, two principal physical mechanisms responsible for this phenomenon were discussed. Proposed by Rishbeth and Garriot (1964) the first mechanism explains Doppler shift oscillations as a result of variations in the phase path brought about by the vertical motion of the ionosphere as the whole associated with the east-west component of the pulsation electric field. According the second one (Poole et al., 1988), oscillations of the Doppler shift of radio waves are caused by compressions and rarefactions of the ionospheric plasma associated with field aligned component of the pulsation magnetic field. Previous observations did not allow choosing the predominant mechanism because of a scanty statistical material. The use of the international ground-based network of two-frequency receivers of the navigation GPS system, consisting of no less than 900 sites and supplying data to Internet, opens up an principally new possibilities of a global continuous monitoring of ionospheric disturbances of different types. Thus, the objective of studies is the analysis of wave signatures measured by using the global detector technology (GLOBTEC) developed by Afraimovich (2000) on the basis of the total electron content (TEC) measurements carried out by GPS system.

GPS technology provides temporal variations of TEC ($I(t)$) in the ionosphere on the basis of measurements of a phase difference between two coherent radio frequencies transmitted by a constellation of 24 satellites. Two criteria were applied here to select pulsations from background variations of TEC. The first criterion is a requirement for an amplitude of detrended TEC variations ($dI(t)$) to exceed a certain threshold (in this case 0.1 TECU ($10^{16}$ el/m$^2$)). This criterion allows to separate records with quiet and disturbed TEC variations. After that disturbed TEC variations are examined with the second criterion which is a requirement for detrended TEC variations to be close to monochromatic oscillations. For this purpose an amplitude spectrum for every $dI(t)$ record is computed and if an integral spectrum in the frequency band of 0.5 mHz located symmetrically relatively the spectral peak exceeds remained part of the total spectrum located outside this band by a factor 2 or more then variations are considered to be the pulsations. Figure 8 presents examples of an application of discussed criteria for the TEC records without pulsations (Figure 8 a, b, c) and with pulsations (Figure 8 d, e, f). In order to provide good statistics, about $3\cdot10^7$ TEC records were analyzed. These records were chosen for 30 days with different levels of geomagnetic activity, the total number of receiving sites in the GPS network being varied from 100 to 300. Analysis has shown that only $0.1\%$ of the total records were characterized as TID pulsations. However, the large absolute figure ($3\cdot10^7$) of pulsation events allowed to study their climatology. Figure 9a presents number of events versus the module of $D_s$-index of magnetic activity. It is seen that probability to observe pulsations are higher for magnetically quiet days compared with disturbed ones. This result seems to be unexpected, if to take into consideration a good correlation between ionospheric and magnetic pulsations observed in previous papers.
7. Comparison of travelling ionospheric disturbance measurements with thermosphere/ionosphere model results.

In the previous years the propagation of AGWs in the neutral atmosphere and their ionospheric signature (TIDs) were studied both experimentally and theoretically. In order to describe a behavior of the ionospheric F region on the basis of the interactions between the thermosphere and ionosphere the comprehensive numerical ionosphere/thermosphere model (CTIM) has been developed by scientists of the University of Sheffield and University College London [Fuller-Rowell et al., 1987]. This model was used to study the atmospheric and ionospheric response to a single short burst of enhanced ion convection at high latitudes [Millward et al., 1993]. A modeling has revealed a large-scale AGW moving equatorward from a source in the auroral zone. The wave propagates to midlatitudes creating a TID. Changes in the electron content (\(N_eF\)) and altitude (\(h_mF\)) of the F peak during the passing of AGW were studied. These parameters can be computed from experimental ionograms, therefore results of the ground based vertical sounding of the ionosphere may be directly used to examine validity of this model.

Nowadays, besides the considered above classical mechanism of the TID’s origination, another mechanism based on electrodynamic processes in the night ionospheric F-layer is actively discussed [Beach et al., 1997, Miller et al., 1997]. It is known that AGW may induce electric fields in the F region of the ionosphere. During the daytime the high conductivity of the E region short out these fields. At night, however, the conductivity of the E region decreases significantly because of decreasing the electron content allowing F region electric fields to develop. The generation of the electric fields alters the ionospheric response to AGW. The electric fields produce cross-field drifts, the plasma is not longer confined to travel along the magnetic field lines and the electron densities generated by AGW may be quite different than the CTIM model predicts. Besides, it has been shown [Perkins, 1973] that for some directions of AGW propagation the Perkins instability can be developed and then the F region ionization moved up and down in a regular wave-like pattern. Thus, the another objective is the experimental study of a response of the ionospheric F-layer to the passage of AGW and comparison of it with modeling results.

For the comparison of results of the CTIM modeling and ionospheric vertical sounding, night observations of TIDs in the F region of the ionosphere were carried out since June 2000 till May 2001 by digital multi-functional ionosonde BASIS installed at Institute of Ionosphere (Almaty, 76°55’ E, 43’15’ N). In Figures 10a, 10b temporal variations of \(h'(t)\) (of the extraordinary component of reflected signals) and \(f_oF(t)\) respectively are shown for a night of 26-27 Nov., 2000 characterized by high level of magnetic activity (\(\Sigma K_p = 28’\)). The large magnetic storm with sudden commencement has began at 05.54 UT on 26 Nov., 2000 and lasted several days. These plots reveal periodical variations parameters considered. Significant part of conducted sessions showed similar wave structures on the \(h'(t)\) variations observed throughout the entire night, but corresponding \(f_oF(t)\) variations were less discernible as we can see in Figure 10. Amplitudes of \(h'(t)\) and \(f_oF(t)\) variations varied from night to night but these variations were always in about antiphase. From the set of \(h'(t)\) there was evidence of downward phase propagation of observed waves.

Millward et al. [1993] parameterized TID in the CTIM model by examining several quantities: \(h_mF\) and \(N_eF\), the height and electron density respectively of the F-layer peak, and the vertical \(N(h)\) profile. In order to compare modeling and present experimental results we converted ionograms into height profiles of electron content \(N(h)\)-profiles) using the accurate method of J.A. Titheridge [Titheridge, 1985]. Variations of the electron content at specific altitudes and total electron content below the F- region peak were computed from \(N(h)\)-profiles and plotted in Figure 10c and 10d respectively. Figure 11 presents a sequence of variations of the plasma frequency with a height for the same observation on November 26-27, 2000. The plasma frequency \(f_o\) is related with the electron content \(N\) as

\[
N = 1.24 \cdot 10^4 f^2, 
\]

where \(f\) is expressed in MHz and \(N\) – in el/cm\(^3\).

Comparing Figures 10a and 11 it can be seen that the ionosphere is lifted by the positive crest of the wave, the electron density in the F peak being decreased and the F-layer thickness increased at the upper position of the F-layer. The informative picture of behaviour of the F-layer in the course of the AGWs passing over a measurement site can be obtained if temporal variations of the height of the F-layer peak (\(h_mF\)) and its critical frequency (\(f_cF\)) are plotted as a hodograph. Figure 12 shows typical examples of hodographs where adjacent points are separated by an interval of 30 min and arrows indicate the direction of running the process. Every hodograph presents several periods of the \(h_mF\) and \(f_cF\) variations. In spite of their different forms, most hodographs have some common features. An irregular hodograph is shown in Figure 12a. All other hodographs demonstrate elliptically polarized trajectories with clockwise rotation. The eccentricity of the ellipses varies from event to event (for example, hodographs shown in Figure 12c are almost circularly...
polarized) but the tilt of the main axis lies in a narrow angular range. Figure 12d shows the result of a superposition of the $h_mF$ and $f_m$ variations caused by passing AGWs and a linear trend of these parameters in the course of the measurements. The eccentricity of the ellipse and the tilt of the main axis are defined by a phase difference between $h_mF$ and $f_m$. Such a character of the F-layer behavior is remarkably consistent with results of a modeling study [Millward et al., 1993]. Figures 6, 8 of this paper reveal the ionospheric response to the passing AGW. This modeling response looks like the experimental response presented here in Figures 10, 11. Millward et al. [1993] gave an explanation of the physical processes running at the thermosphere and ionosphere, which are responsible for the F-layer behavior in the course of passing AGW over the site of observation.

The changes occurring within the ionosphere due to the AGW passing over the site of observation are principally caused by a redistribution of the plasma and are not due to changes in the production or loss processes. The redistribution is caused by the motion of the ions along the magnetic field line. The field aligned velocity of ions can be expressed as $V_{\parallel} = U_{\parallel} + D_{\parallel}$ where $U_{\parallel}$ is the field aligned component of the neutral wind caused by AGW, $D_{\parallel}$, referred to as the diffusion term, is the sum of the density gradient, temperature gradient and gravity terms. Above 300 km the diffusion term increases in influence with increasing a height.

The ion flux height profiles plotted in Figure 7 of Millward et al. [1993] indicate the redistribution of plasma that occurs due to effects described above. Maximum upward flux occurs near the time of a crest in the wave of height variations, producing increase in $h_mF$. The maximum flux, in this plot, lies at an altitude above the F peak. Also, it can be seen that the magnitude of the gradient in the flux, along the tube, is greater above the flux peak than below it. This divergence in the field-aligned flux is responsible for the decrease in $N_mF$, which reaches a minimum at the time of a maximum in $h_mF$. Downward ion fluxes of a similar magnitude and a similar divergence in the field-aligned flux lead to the density profiles located at lower altitudes.

Thus, this study shows that the F-layer behavior during the a magnetic storm is remarkably consistent with results of a modeling study of the atmospheric and ionospheric response to a burst of enhanced ion convection at high latitudes.

It is of interest to study a TID signature obtained with a satellite technique, which allows measuring the total electron content (TEC) along the line of sight path from the observer to a satellite. Our data do not allow having TEC above F peak but only below it. However, it will be later shown that F region below F peak gives the main contribution to TEC variations caused by TID. Thus, to simulate TID measurements by a satellite, TEC below F peak was computed and results are presented in Figure 10d. It can be seen that the same periodical structure presents in the TEC record but the long period variation ($\lambda \approx 4.7$ hours) is hardly visible on the background of short period variations. The reason of that is as follows. From delay of the same phase of TID between various altitudes we estimated a vertical wavelength as $\lambda_v \approx 1400$ km. This is large compared with the thickness of the F-layer, and thus the passage of the AGW lifts the whole of the F-layer in phase practically. Small decrease of TEC in the upper position of the F-layer that should be caused by the decrease the $N_mF$ is compensated by increasing the layer thickness leading to minimal variations of TEC.

It is known [Hines, 1960] that the upward energy flux of the AGWs remains constant in the nondissipative atmosphere. The wave amplitude increases with height because the upgoing wave propagates into a region of exponentially decreasing density of the atmosphere. Clearly, this increase cannot be maintained indefinitely. On thermospheric altitudes processes of dissipation such as the temperature conductivity and molecular viscosity begin to compete with growth of the amplitude leading to creation of a maximum on the amplitude height profile. It seems that altitude of the maximum amplitude of AGW differs from that of TID maximum because the electron content height profile superimposes on the AGW height profile. Thus, it is of great importance for the task of TIDs parameterization to study height profiles of TIDs from experimental ionograms.

For this purpose the 5-min-interval sequences of the electron content height profiles were used. From these profiles the temporal behavior of the electron content at series of specific heights separated with interval of 10 km was computed as in Figure 10c. The wave amplitude defined as a half of the peak-to-peak amplitude was computed for every altitude. It allowed obtaining the height profiles of the wave amplitude and its dependence on a season and magnetic activity. The typical height profiles of the TID amplitude for three successive nights are plotted in Figure 13. The total number of 64 height profiles was analyzed. The common shape of these height profiles can be approximated as a parabola with its average thickness (defined at the level of 0.5 maximum amplitude) estimated as $\sim 60$ km. An altitude of the maximum amplitude was scattered between 200 and 300 km with the most probable value of $\sim 240$ km (in 62.5% of all events the altitude was ranged between 220 and 260 km). No evident seasonal dependencies of the shape and position of the height amplitude profile were noticed. The weak dependence on the magnetic activity was pointed out. During magnetic storms there was a tendency for the maximum amplitude, its altitude, and the thickness of the height amplitude profiles to be larger than those for the quiet magnetic conditions.

8. Conclusions

Spectra of AGWs at the mesopause and thermosphere were compared on the basis of data of nightglow emission and ionospheric (virtual heights of sounding radio signals reflections) observations conducted since October 1997 till February 2001. Two types of virtual height variations (periodical and quasi-stochastic) were found to exist in the thermosphere. The first one is related with AGWs identified by the downward direction of wave phase propagation. The
seasonal dependence of AGW presence was found. AGWs were presented during 70-85% of observations conducted in a period since October till March. In the summer, probability of their observations was only 20-40%. The rest part of observations revealed the quasi-stochastic character of virtual height variations. Spectral analysis of simultaneous AGW records for the mesopause and thermosphere revealed a good coincidence of spectral peaks for these atmospheric layers. Two groups of spectral peaks were found in the most spectra both for the mesopause and for thermospheric altitudes. Periods of the first group were ranged in 4 - 8 hours and centered on a period of 6 hours. This group was identified with tidal oscillations of the atmospheric layers. The second group including periods of 0.7-4 hours is considered to be a manifestation of AGWs propagation at altitudes considered. Vertical phase velocities of waves were determined from virtual height variations obtained for different sounding frequencies. The phase velocities were found to increase when the period of a wave decreases.

Our findings bear witness to the determining role of geomagnetic disturbances in the formation of the spectrum of traveling ionospheric disturbances. This conclusion is based on substantially more extensive (than obtained earlier) statistical material. It spans periods with a different level of geomagnetic disturbance, and has a global character. The analysis has been made for a set of 100 to 300 GPS stations for 10 days with a different level of geomagnetic activity ($Dst$ from 0 to –350 nT; the $Kp$ index from 3 to 9). It was found that power spectra of daytime TEC variations in the range of 20–60 min periods under quiet conditions have a power-law form with the slope index $k = -2.5$. With an increase in the level of magnetic disturbance, there is an increase in the total intensity of TIDs, with a concurrent kink of the spectrum caused by an increase in oscillation intensity in the range of 20–60 min. The TEC variation amplitude is found to be smaller at night than during the daytime, and the spectrum decreases in slope, which is indicative of a disproportionate increase in the amplitude of the small-scale part of the spectrum. It was found that an increase in the level of geomagnetic activity is accompanied by an increase in the total intensity of TEC; however, it does not correlate with the absolute level of $Dst$, but rather with the value of the time derivative of $Dst$ (a maximum correlation coefficient reaches –0.94). The delay in the TID response of the order of 2 hours is consistent with the view that TIDs are generated in auroral regions, and propagate equatorward with the velocity of about 300–400 m/s.

An analysis of the data has shown that being originated the auroral disturbance induced LS solitary wave with a period of about 1 hour and the front width no less 5000 km traveled equatorward to a distance no less than 1000 km with the average velocity of about 200 m/s. The TEC disturbance, showing mainly a decrease of the electron content in the vicinity of the F2-layer maximum, correlates with an increase of the emission rate in the optical band, with the temporal shift being different for different ionospheric altitudes. For the first time, simultaneous response of the mesopause and thermosphere on a large geomagnetic storm is obtained at two spaced sites. A good correlation was shown to exist between TEC and optical emission variations.

Simultaneous observations of the ionosphere carried out at distant sites and night airglow at the mesosphere showed that variations of virtual heights of the radio wave reflections from the ionosphere and emission rate may be explained on the basis of presence of low frequency wave components with periods of 4-8 hours identified with the harmonics of the tidal wave and high frequency wave components with periods below 4 hours presenting large-scale TIDs. Amplitudes of tidal harmonics change from night to night but very high correlation between these harmonics observed at greatly spaced sites was recorded. Correlation of large-scale TIDs for the same sites was noticeably less.

The climatology of total electron content (TEC) pulsations based on statistics of $3\cdot10^8$ TEC records obtained from a global GPS network is considered. Two criteria were developed to select pulsations from background variations of TEC. Analysis has shown that only ~0.1 % of the total records were characterized as TID pulsations. However, the large absolute figure (~3-10³) of pulsation events allowed to study their climatology. A comparison number of events with the module of $Dp$-index of magnetic activity has shown that the probability to observe pulsations are higher for magnetically quiet days compared with disturbed ones. The maximum probability to observe pulsations corresponds to the local noon. In order to estimate an area covered by pulsations, there were computed various distances ($dR$) between points available where pulsations were presented in the certain temporal interval. It seems that pulsations are localized into space. In spite of a long tail of the distribution extending 2100 km, most of events are restricted by the distance of 500-600km.

The experimental study of a response of the midlatitude night ionospheric F layer to passing atmospheric gravity waves is carried out. The ionograms were analyzed for temporal variations of the virtual height ($h(t)$) at a series of specific frequencies, critical frequency of the F-layer ($f_o F_i$), and height profiles of electron content ($N(h)$-profiles). Significant part of observations showed definite wave structures on the $h(t)$ variations observed throughout the entire night, but corresponding $f_o F_i$ variations were less discernible. These $h(t)$ and $f_o F_i$ variations were always in antiphase. From the $h(t)$ there was evidence of downward phase propagation of the observed waves. The temporal behavior of the electron content at series of specific heights allowed obtaining the height profiles of the wave amplitude ($eV/m^2$) and to study its dependence on a season and magnetic activity. The total number of 64 height profiles was analyzed. The common shape of these height profiles can be approximated as a parabola with its average thickness (defined at the level of 0.5 maximum amplitude) estimated as ~60 km. An altitude of the maximum amplitude was scattered between 200 and 300 km with the most probable value of ~ 240 km (in 62.5% of all events the altitude was ranged between 220 and 260 km). No evident seasonal dependencies of the shape and position of the amplitude height profile were noticed. The weak dependence on the magnetic activity was pointed out. During magnetic storms there was a tendency for the maximum amplitude, its altitude, and the thickness of the height amplitude profiles to be larger than those for the quiet magnetic conditions.

A consequence of $N(h)$-profiles calculated for a period of the passing wave showed them to move up and dawn in phase with the passing wave. As the F layer is lifted by the positive surge in gravity wave, an electron content at the F peak decreases, the slab thickness being increase. Subsequently, the opposite happens as $h_o F$ falls below its equilibrium
value. Such a character of the F layer behavior is remarkably consistent with results of a modeling study of the atmospheric and ionospheric response to a single short burst of enhanced ion convection at high latitudes performed with the CTIM model.

References


J.E. Titheridge, Ionogram analysis with the generalized program Polan, National Geophysical Data Center, Boulder, CO USA, 1985, p. 189.


Fig. 1. Examples of quasi-periodic (a) and quasi-stochastic (b) variations virtual heights of ionospheric reflections at a number of sounding (specific) frequencies ($f_1, f_2, \ldots$). A lower curve is a variation at a frequency of 2.5 MHz. Consequent curves are variations at frequencies of 3.5 MHz, 4.5 MHz \ldots
Fig. 2. Detrended temporal variations of the virtual heights and emission ratio at Almaty.
Fig. 3. An example of estimating parameters of TID spectra for magnetically quiet and disturbed periods.
Fig. 4. The initial time-series of slant TEC, $I(t)$, at GPS stations ZWEN, ARTU, KSTU for satellite PRN25 on 6 April, 2000 (b) and TRAB (c); and detrended ones, $dI(t)$, (e), and (f). Panels (a) and (b) represent $I(t)$ and $dI(t)$ variations at the station YAKZ for satellite PRN30. Geographical co-ordinates of subionospheric points for every station at $t_{\text{min}}$ are plotted at panels (a), (b), (c). Diamonds at temporal axes denote moments, $t_{\text{min}}$, of minimum $dI(t)$.
Fig. 5. As in Fig. 4, but for GPS stations IRK (a, d), SELE (b, e), KUMT, KIT3, and URUM (c, f). For comparison, thin lines at the panel (d) show behaviour of the 630 nm emission rate (A(t)) and the 577.7 nm emission rate (B(t)) recorded by the instrument FENIX and filtered from initial data (Fig. 6a, curves 1, 2, respectively), as it was done for TEC data, I(t). Behaviour of the 866.5 nm emission rate (C(t)) recorded by the instrument MORTY and filtered from initial data (Fig. 6b), as it was done for TEC data, I(t).
Fig. 6. Variations of the 630 nm and 577.7 nm emission rates (curve 1, 2, respectively) during magnetic storm of 6 April, 2000 in universal (UT)) and local (LT) times (a). Variations of the nightglow emissions at spectral band of 360-410 nm (curve 4) and 720-830 nm (curve 5) (b). For comparison, variations of the 630 nm emission rate (curve 3) and emission rate in the band of 360-410 nm (curve 6) corresponded to the magnetically quiet night of 5 April, 2000 are plotted. Data were obtained by FENIX instrument.
Fig. 7 Detrended temporal variations of virtual heights of F-layer at Novosibirsk and Almaty.
Fig. 8. Examples of an application of criteria for selection of the TEC pulsations. (a, b) Initial and detrended TEC variations respectively for an event without pulsations. © Corresponding amplitude spectrum. (d, e, f) Similar to (a, b, c) except that this event is characterized with pulsations. Thin horizontal lines in (b, e) are thresholds for the amplitude criterion. Thin vertical lines in (c, f) restrict the frequency band near the largest spectral peak.
Fig. 9. Scatter plots of number of events versus: a) the module of $D_s$-index of magnetic activity, c) a distance between the points where pulsations are presented in a certain temporal interval, b) a diurnal distribution of moments corresponding to the maximum amplitude of pulsations into a certain packet (mark $t_{\text{max}}$ in Figure 8e).
Fig. 10. Plots of the temporal variations of: a) virtual heights (x-component of the ionospheric signal) corresponding to specific frequencies of 2.5 MHz, 3.5 MHz, 4.5 MHz, 5.5 MHz, and 6.5 MHz, b) critical frequencies of the ordinary ($f_o$) and extra-ordinary ($f_x$) components, c) the electron content at series of heights $h= 190$ km, 220 km, 250 km, 270 km, and 300 km, d) the total electron content below the F-layer peak.
Fig. 11. Plasma frequency height profiles at 23.30 h, 00.00 h, 00.30 h, and 01.00 Almaty standard time for November 26-27, 2000.
Fig. 12. Typical examples of hodograph show the time evolution of the $h_mF$ versus $f_{cr}$. 