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Planetary and gravity wave signatures in the *F*-region ionosphere with impact on radio propagation predictions and variability

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The aim of this work within the WP 3.1 of the COST 271 Action is the characterization of the variability introduced in the *F*-region ionosphere by 'Planetary Wave Signatures' (PWS) and 'Gravity Wave Signatures' (GWS). Typical patterns of percentage of time occurrence and time duration of PWS, their climatology and main drivers, as well as their vertical and longitudinal structure have been obtained. Despite the above characterization, the spectral distribution of event duration is too broad to allow for a reasonable prediction of PWS from ionospheric measurements themselves. GWS with a regular morning/evening wave bursts and specific GWS events whose arising can be predicted have been evaluated. As above, their typical pattern of occurrence and time duration, and their vertical structure have been obtained. The latter events remain in the ionospheric variability during disturbed days while additional wave enhancements of auroral origin occur. However, both types of disturbances can be distinguished.

10.1. INTRODUCTION

Interest in the ionospheric *F*-region variability has increased recently (Forbes *et al.*, 2000; Rishbeth and Mendillo, 2001; Mendillo *et al.*, 2002), partly due to the role that the ionosphere plays in the Earth's environment via coupling processes from above and below, the former being a significant part of the space weather. The variability of the ionospheric *F*-region ranges from time-scales of minutes (*e.g.*, TID's) to long-term changes (solar cycle variations and even secular). Table 1 from Rishbeth and Mendillo (2001) summarizes the possible causes of the ionospheric *F*-region variability. It is widely accepted that the geomagnetic activity is the main cause of the ionospheric variability, although meteorological causes transmitted from below may contribute comparatively. Many of the «meteorological influences» on the ionosphere arise from upward propagating gravity, tidal and planetary waves (Kazimirovsky *et al.*, 2003). Here we discus the main results on 'Planetary Wave Signatures' (PWS) and 'Gravity Wave Signatures' (GWS) as sources of the variability of the *F*-region ionosphere obtained within the COST 271 Action. It should be mentioned that we also studied the effects of gravity and planetary waves on the lower ionosphere (Boskova and Laštovička, 2001; Laštovička, 2001; Laštovička *et al.*, 2003c). The PWS in the *F*-region with an emphasis on their possible sources, time duration and time occurrence patterns, their typical longitudinal size, and their climatology are presented in Section 10.2. Section 10.3 deals with the GWS of non-auroral origin in the *F*-region with an emphasis on their regular occurrence and on other specific events. The last section highlights the most relevant conclusions of our work within the COST 271 Action.

10.2. PLANETARY WAVE SIGNATURES ON THE *F*-REGION

The Planetary Waves (PW) in the Mesosphere/Lower Thermosphere (MLT) (Salby, 1984) may indirectly reach the *F*-region ionosphere and drive PW effects there. The PW modulation of upward propagating tides or gravity waves, the interaction of PW with the strong diurnal/semidiurnal dependence of the ionosphere, and the transmission of PW activity via vertical plasma drift or mean vertical mass transport may explain the arising of PW effects in the *F*-region from the PW activity in the MLT (Laštovička and Šauli, 1999; Pancheva *et al.*, 2002; Altadill and Apostolov, 2003; and references therein). Experimental results show also the vertical propagation structure, from above and below, of such oscillation activity in the *F*-region (Altadill and Apostolov, 2001; Altadill *et al.*, 2001b). The latter case studies assess that PW effects in the *F*-region originated from the PW activity in the MLT propagate upwards. However, these investigations stated that a «*quasi*-periodic» sequence of geomagnetic storms and sub storms and/or large storms can generate wave-like oscillations in the ionosphere as well. Hereafter we call 'Planetary Wave Signatures' (PWS) both effects, the oscillation activity of the ionosphere driven by the PW activity in the MLT and geomagnetic activity. The PWS discussed here have periods of about 2, 5, 10, 13.5, and 16 days, these PWS being an important source of variability of the ionosphere – they may contribute up to 50-60% of the variability of the $f0F2$ in the periodic range 2-35 days (Apostolov *et al.*, 1998).

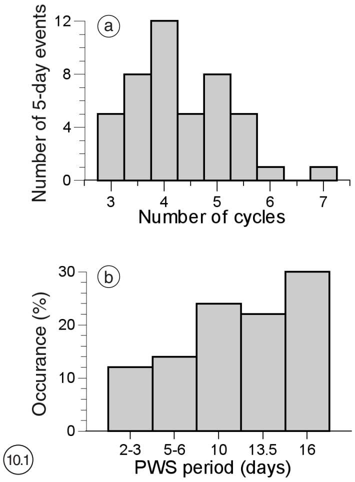
10.2.1. Time duration and time occurrence patterns

An important input to COST 271 is the evaluation of the persistence of PWS in $f0F2$ over Europe (Laštovička *et al.*, 2003a). They found a typical duration of 4 cycles for the 5-day events. The typical duration being of about 3.5 and rather 3 cycles for the 10-day and 16-day events, respectively. So, in terms of numbers of cycles PWS with longer period of oscillation have shorter duration, but they have longer duration in terms of time. However, the spectral distribution of event duration is too broad to allow for a reasonable prediction of event duration (fig. 10.1a), which means that PWS-type oscillations remain to be unpredictable noise in ionospheric predictions until a reasonably reliable combination of external predictors will be found. Laštovička *et al.* (2003b) found quite similar results for stations at middle latitudes in Japan and U.S.A.

By taking into account the average values of event duration and numbers of events found by Laštovička *et al.* (2003a), one can conclude that the 5-day, 10-day and 16-day events manifest themselves during about 16%, 26% and 34% of the time respectively. Altadill and Apostolov (2003) confirmed the latter results at midlatitude global scale and that 2-day and 13.5-day events manifest themselves during about 12% and 22% of the time, respectively (fig. 10.1b).

10.2.2. Longitudinal size pattern

Altadill *et al.* (2001a, 2003) evaluated the zonal structure of PWS in some case studies, and they showed that PWS are large-scale phenomena in the *F*-region. The typical longitudinal size of such events in the mid-latitude *F*-region of the Northern Hemisphere has been obtained recently (Altadill and Apostolov, 2003). They did not distinguish between traveling and standing waves and did not



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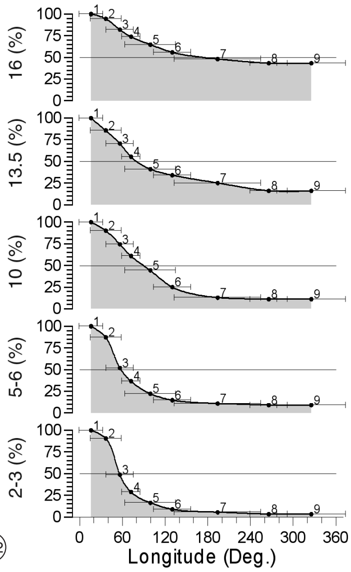


10.2

Fig. 10.1a,b. The top plot shows an example of the typical duration of PWS in terms of number of cycles for the 5-day events (after Laštovička *et al.,* 2003a). The bottom plot depicts the typical percentage of occurrence of PWS events according to their dominant oscillating periods (after Altadill and Apostolov, 2003).

Fig. 10.2. The plots shows the percentage of occurrence of PWS events (*y* axes) referred to the number events found to exist in sector 1 as function of their longitudinal size (*x* axis). The horizontal error bars mean the longitudinal size of the labeled midlatitude sector. The horizontal lines of each plot indicate the assumed threshold for the typical longitudinal size (after Altadill and Apostolov, 2003).

consider the possibility that standing oscillations would not necessarily be seen at a given single sector if the minima in the wave were present in that sector. They compared the coherent PWS at consecutive midlatitude longitudinal sectors and their result may be summarized as follows (fig. 10.2). The PWS with periods of 2-3 and 5-6 days have a typical longitudinal size of 80°. Although they can be observed on a larger zonal scale, it is quite unlikely. PWS with periods of 10 and 13.5 days have a typical longitudinal size of 100°, they being likely observed on a larger zonal scale. PWS with a period of 16 days have a typical longitudinal size of 180°, they being likely observed at global scale.

To some extent the above results contradict the estimation of the scale size of the 'meteorological influences' reported by Mendillo *et al.* (2002), who find that these variations are coherent some 2500 km apart only. By considering PWS as a part of the 'meteorological influences' on the ionospheric variability, the above results indicate that PWS in the *F*-region ionosphere are large scale phenomena (note that a longitudinal scale of 80° at latitude of 50° means a distance of 6000 km), having larger zonal scale for PWS with longer oscillating periods.

10.2.3. Climatology and sources

The typical climatology of PWS in the *f*0*F2* at midlatitudes has been also evaluated within COST 271 Action (Altadill and Apostolov, 2003). From their results one senses that the occurrence of PWS in the $f0F2$ is better expressed during the summer half of the year (fig. 10.3). The latter is better expressed for PWS with shorter period. This is not surprising because the contribution of the PWS to the variability of the $f0F2$ is higher also at that time (Apostolov *et al.*, 1998). However a quite singular pattern is obtained when the seasonal occurrence of PWS in the $f0F2$ is considered in relation to their dominant 'driver'. According to Altadill and Apostolov (2003) these drivers may be the PW activity in the MLT, the geomagnetic activity, and PWS events 'independent' from the above two, there being a very small contribution of solar flux variations to the ionospheric variability at periods of 2-30 days, see also Forbes *et al.* (2000). These results are summarized in table 10.I. The PWS related with the PW activity in the MLT tend to occur according to the climatology of the latter, PWS with shorter period occur during summer half year and those with longer period occur during winter half year. An exception to that is the PWS with a period of 13.5 days, which are related to the geomagnetic activity variations. The PWS related with the geomagnetic activity tend to occur during summer half year. The so-called independent PWS events tend to occur during summer half year also. The evaluation of the possible 'main driver' of the PWS in the ionosphere suggests that geomagnetic activity variations play the most important role (Altadill and Apostolov, 2003). This is especially clear for the 13.5-day events. The geomagnetic activity variations practically drive 100% of the latter events in the ionosphere. The geomagnetic activity variations can drive at least 20% of the 2-3-day events, at least 30% of the 5-6-day events, 20-70% of the 10-day events, and 25-65% of the 16-day events. A likely candidate for the 'independent' events may be the non-linear interaction or the amplitude modulation between different PWS (*e.g.* Altadill *et al.*, 2001b; Pancheva *et al.*, 2002). The PW activity in the MLT can drive about 20-30% of PWS in the ionosphere with periods near 2-3, 5-6, 10, and 16 days. Note that the above percentages agree with those reported by Forbes *et al.* (2000), which refer to the 'meteorological influences' on the ionospheric variability.

10.3. GRAVITY WAVE SIGNATURES ON THE *F*-REGION

The Atmospheric Gravity Waves (AGW) can generate disturbances in the ionosphere, the latter being mainly driven by heating produced by electric currents, energetic particle precipitation and mechanical forces in the auroral ionosphere. Other sources of AGW disturbances in the ionosphere are from lower- and middle-atmosphere associated with regions of turbulence and wind shear (Hunsucker, 1987; Hocke and Schlegel, 1996), and strong tropospheric events (Šauli and Boška, 2001). There are a variety of studies that show the moving Solar Terminator as a source of such type of disturbances (Somsikov, 1995; Galushko *et al*., 1998). Moreover, several studies showed the arising of AGW in the ionosphere as a consequence of solar eclipses. The latter can contribute to a gravity wave field and build up a wave front that may produce ionospheric disturbances (Chimonas and Hines, 1970; Liu *et al*., 1998). Solar eclipses can generate temperature disturbances *in situ* in the thermosphere and electron density changes *in situ* in the ionosphere and such disturbances will propagate as a wave (Müller-Wodarg *et al*., 1998). Hereafter we call Gravity Wave Signatures (GWS) to the above discussed disturbances in the *F*-region with characteristics of AGW. Our results were obtained mainly during quiet periods of geomagnetic activity. However, some important results were obtained during campaign «HIRAC/SolarMax» (Feltens *et al*., 2001). As an input to the COST 271 Action we will emphasize mainly on regular occurrence of GWS and on specific events whose arising can be predicted.

10.3.1. Specific GWS events

Specific GWS events arising in the *F*-region have been evaluated by preparing ionospheric campaigns of rapid sequence sounding in order to study the source-response relationships between production and

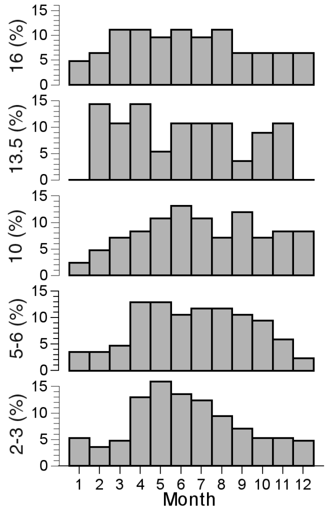
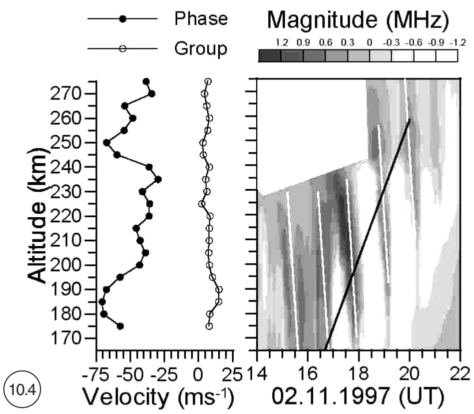


Fig. 10.3. Percentage of occurrence of PWS events (y axes) as function of month during the time interval 1983-2001 (adapted from Altadill and Apostolov, 2003).

Table 10.I. Percentages of seasonal occurrence of the different PWS in the $f0F_2$ according to their possible drivers. WIN means from November to February, EQU means March, April, September and October, and SUM means from May to August. MLT means PWS driven by PW activity in the MLT, GEO by the geomagnetic activity and IND means PWS events 'independent' from the above two (after Altadill and Apostolov, 2003).

PWS		2-3	5-6	10	13.5	16
IND	WIN	5	4	2	0	3
	EQU	4	11	0	0	3
	SUM	15	13	5	0	3
MLT	WIN	5	8	11	0	10
	EQU	14	6	5	0	11
	SUM	13	7	4	0	5
GEO	WIN	9	3	10	25	11
	EQU	12	21	30	38	21
	SUM	23	27	33	37	33

loss mechanisms, and dynamics. These events are related to solar eclipses and the passage of cold tropospheric fronts (*e.g.,* Altadill *et al*., 1999, 2001c; Boška *et al*, 2000; Boška and Šauli, 2001; Šauli, 2001a,b). The main results on these GWS events are related to their vertical structure, time life, degree of variability and their dominant oscillating periods (fig. 10.4). Although the source of disturbances are quite different, the ionosphere reacts at very similar periods (between 60 to 80 min), their amplitudes in the plasma frequency range from 0.2 to 1.2 MHz (showing a high degree of variability), their life time is of about 4-6 cycles of oscillation (up to 6 h), and their energy propagates vertically at an average speed of



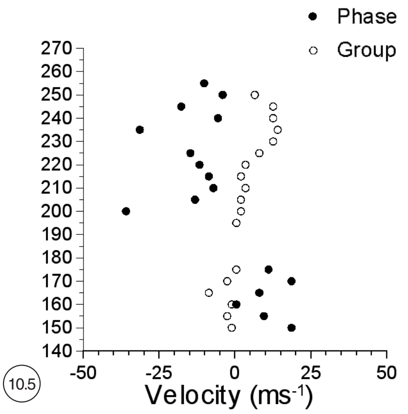


Fig. 10.4. Vertical structure of a GWS event caused by a cold front passage during 2 November 1997 as observed above Ebro station (40.8°N, 0.5°E). The left plot shows the vertical phase and group velocities of the wave packet with dominant period of 75 min as function of the altitude. The right plot shows the disturbance of this event caused in the plasma frequency as function of time and altitude, where the black line simulates the energy progression of the wave with an averaged velocity of 8 ms^{-1} and the white lines simulate their phase progression with an averaged velocity of -47 ms^{-1} (adapted from Altadill *et al.,* 1999).

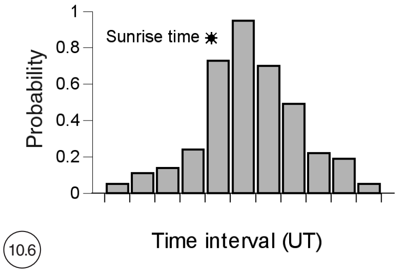
Fig. 10.5. Vertical structure of a GWS event observed during solar eclipse 11 August 1999 above Průhonice observatory (49.9°N, 14.5°E). The plot shows the vertical phase and group velocities, time occurrence of central period of the wave packet with dominant period of 85 min as function of the altitude (adapted from Šauli, 2001b).

about 5-10 ms^{-1}. However, their vertical structure is quite different. Whereas the GWS caused from cold fronts propagates upwards in the *F*-region (fig. 10.4), the GWS caused by solar eclipse originates at transition region between the *F*1- and *F*2-layers and it propagates upwards and downwards simultaneously from that level (fig. 10.5) – see Altadill *et al.* (2001c), Šauli (2001a). Thus the vertical structure of GWS displays different patterns according to their sources of origin.

The GWS caused by tropospheric fronts are due to dynamics from lower atmospheric levels, that is why GWS propagate upwards. The GWS caused solar eclipses are due to the cooling/heating processes linked with the decreasing/increasing solar radiation that leads to a reduction/augment of the scale height for both plasma and neutrals. This fact causes a downward/upward motion of plasma and neutrals as well as of *F*1 production peak and of the transition region between *F*1- and *F*2-layers, that is why the source of disturbance is located in that region from where its energy propagates upwards and downwards.

10.3.2. Regular occurrence of GWS

It was already mentioned that solar terminator acts as a source of GWS in the *F*-region, and this is a regular phenomenon occurring at sunrise/set times. That is why the diurnal variation of the activity of GWS related with that has been evaluated (Boška *et al.*, 2003). They found systematic occurrence of these events during sunrise time and lasting several hours (fig. 10.6). Diurnal variations of AGW activity during periods of low solar and geomagnetic activity (1996, 1997 years) show a clear enhancement during and several hours after sunrise. The observed internal AGW (with main periods between 60 and 75 min) propagates with significant vertical component through ionosphere from a source located at altitude of 180-220 km. Vertical components (amplitude, phase and group velocity) of the typical structure with dominant period 72 min are shown in fig. 10.7. Similar effects of GWS were observed in a period range 50-100 min during the period of high solar activity (2000-2001). Particular wave enhancements corresponding to solar terminator movement on 24 April 2001 are shown on the wavelet power spectra of the electron concentration at altitude 230 km (fig. 10.8). Amplitudes of the observed oscillations reach the maximum usually above 200 km and below *F*-layer peak, with typical value in electron concentration of 0.3-0.5 $[10^{11}\mathrm{m}^{-3}]$, in the plasma frequency range from 0.2 to 1.2 MHz, their time life is of about 4-6 cycles of oscillation, and their energy propagates vertically at an average



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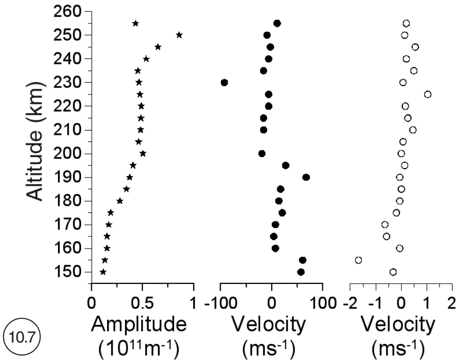

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Fig. 10.6. Time variation of the probability of existence of a GWS event with dominant period of 61 min observed above Průhonice station (49.9°N, 14.5°E) during 31 October 1997 (adopted from Boška *et al.,* 2003).

Fig. 10.7. Altitude variation of the amplitude (*left*), phase velocity (*middle*) and group velocity (*right*) obtained for the wave event with dominant period of 72-min observed during October 12, 1996 in the Průhonice data (adopted from Boška *et al.,* 2003).

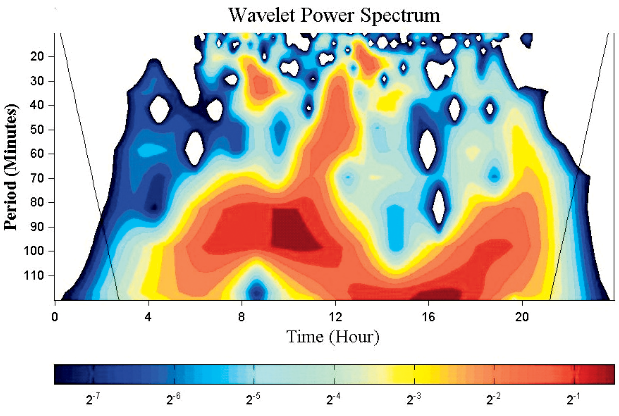

Fig. 10.8. Wavelet power spectra of electron concentration variation on 24 April 2001 at 230 km with substantial intensification of wave-like activity in dawn and dusk hours at period range 70-100 min.

speed of a few ms^{-1}. Their vertical structure (fig. 10.7) recalls that described for GWS caused by solar eclipses (fig.10.5). One senses that GWS originates at altitudes of about 180-200 km, *i.e.* near the transition region between the *F*1- and *F*2-layers and it propagates upwards and downwards simultaneously. As a consequence of the above discussion, the heating processes linked with the rapid increase of the solar radiation during sunrise/set can act as a source of turbulence in the ionospheric *F*-region and generate GWS in the electron density (see also Somsikov, 1995).

Effects of the morning and evening wave bursts were observed during all campaigns and seem to be a regular wave enhancement in the *F*-region ionosphere. Results show that GWS that could be related to the solar terminator remains in the spectra during day of storm and they show similar vertical structures as during previous days while additional strong wave enhancements of auroral origin occur in the electron concentration. During the periods of high solar and geomagnetic activity (1991, 2001), a substantial intensification of AGW activity, associated with the response of magnetosphere to a sharp increase of solar wind, was observed. The amplitudes of the GWS during the latter periods increase twice to three times compared to the GWS detected during geomagnetic quiet time. Campaign HIRAC/SolarMax (23 April-29 April 2001) started during a period of low geomagnetic activity and finished during a magnetic storm. The clear difference between GWS and disturbances of auroral origin was studied and presented (Šauli, 2001a,b; Šauli and Abry, 2003; Šauli *et al.*, 2003a,b). Wave structures occurring during a geomagnetic storm do not have a vertical component of phase and group velocities. Onset time of the particular wave structure at distant observatories confirm the horizontal propagation of the structure.

10.4. SUMMARY AND CONCLUSIONS

The research work carried out under COST 271 Action as refers to the PWS in the periodic range 2-16 days and GWS leads to the following conclusions.

PWS in the midlatitude *F*-region ionosphere may contribute up to 50-60% of the total variability in the period range 2-35 days. The latter is better expressed during summer half year. The typical time of occurrence of PWS with periods from 2 to 16 days is from 12 to 35% respectively, and their typical duration ranges from 4 to 3 cycles of oscillation, respectively. However, the spectral distribution of event duration is too broad to allow for a reasonable prediction of event duration, which means that PWS remain to be unpredictable at present from ionospheric measurements themselves.

PWS in the midlatitude *F*-region ionosphere are large-scale phenomena. Their typical longitudinal size ranges from 80° for PWS with periods of 2-3 and 5-6 days to 180° for PWS with periods of 16 days, those being observed on a larger zonal scale and even global.

One senses that geomagnetic activity variations are the main drivers of PWS in the midlatitude *F*-region ionosphere. However, PW activity in the MLT may contribute comparatively in some cases, there being a very small contribution of solar flux variations to the ionospheric variability at periods of 2-30 days. The PWS related with the geomagnetic activity tend to occur during summer half year. The so-called independent PWS events tend to occur during summer half year also. The PWS related with the PW activity in the MLT tend to occur during summer half year for PWS with shorter period, and those with longer period tend to occur during winter half year. The latter events display a distinct vertical structure with upwards energy propagation.

GWS in the midlatitude *F*-region ionosphere with a regular occurrence and specific GWS events whose arising can be predicted have been evaluated. The results were obtained mainly during quiet periods of geomagnetic activity. However, some important results were obtained during disturbed periods as well.

The specific GWS events are those caused by meteorological cold fronts passages and by solar eclipses. Despite the different source of disturbance, the ionosphere reacts at very similar periods, their amplitudes in the plasma variations show a high degree of variability, their time life is up to 6 h, and their energy propagates vertically at an average speed of a few ms^{-1}. Their vertical structure however is quite different, the GWS caused cold fronts propagates from below in the *F*-region and the GWS caused by solar eclipse originates at transition region between the *F*1- and *F*2-layers and it propagates upwards and downwards simultaneously from that level.

Morning and evening wave bursts are regularly observed in the *F*-region ionosphere during all ionospheric sounding campaigns, showing that these GWS could be related to the solar terminator. Their typical duration is about 4-6 h, their amplitudes in the plasma variations show a high degree of variability, their vertical structure is similar to the GWS caused by solar eclipse, it originates at transition region between the *F*1- and *F*2-layers and it propagates upwards and downwards simultaneously from that level. The GWS related to the solar terminator remain in the spectra during day of storm and shows similar vertical structures as during quiet days while additional strong wave enhancements of auroral origin occur. The latter however do not have vertical energy propagation. So that sunrise terminator-related GWS events are a good candidate for being included into ionospheric prediction algorithms.

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REFERENCES

ALTADILL, D. and E.M. APOSTOLOV (2001): Vertical propagating signatures of wave type oscillations (2- and 6.5-days) in the ionosphere obtained from electron density profiles, *J. Atmos. Sol.-Terr. Phys*., **63**, 823-834.

ALTADILL, D. and E.M. APOSTOLOV (2003): Time and scale size of planetary wave signatures in the ionospheric *F*-region. Role of the geomagnetic activity and mesosphere/lower thermosphere winds, *J. Geophys. Res*., **108** (A11), 1403, doi:10.129/2003JA010015.

ALTADILL, D., J. BOŠKA, J. G. SOLÉ and L. F. ALBERCA (1999): Short-time fluctuations in the *F*-region electron density, in *COST 251/IITS Workshop on the Impact of the Upper Atmosphere on Terrestrial and Earth-Space Communications, Scientific Report*, 22-25 March 1999, Madeira, Portugal, COST Document COST251TD (99)008, 187-191.

ALTADILL, D., E.M. APOSTOLOV, J.G. SOLÉ and L.F. ALBERCA (2001a): Preliminary results of the zonal structure of 6 days oscillation in the *f*0*F*2 at middle latitude Northern Hemisphere, *Bulg. Geophys. J.*, **27** (1/4), 115-123.

ALTADILL, D., E.M. APOSTOLOV, J.G. SOLÉ and CH. JACOBI (2001b): Origin and development of vertical propagating oscillations with periods of planetary waves in the ionospheric *F*-region, *Phys. Chem. Earth (C)*, **26** (6), 387-393.

ALTADILL, D., J.G. SOLÉ, and E.M. APOSTOLOV (2001c): Vertical structure of a gravity wave like oscillation in the ionosphere generated by the solar eclipse of August 11, 1999, *J. Geophys. Res.*, **106**, 21419-21428.

ALTADILL, D., E. M. APOSTOLOV, CH. JACOBI and N.J. MITCHELL (2003): 6-day westward propagating wave in the maximum electron density of the ionosphere, *Ann. Geophysicae*, **21**, 1577-1588.

APOSTOLOV, E.M., D. ALTADILL and R. HANBABA (1998): Spectral energy contributions of *quasi*-periodic oscillations (2-35 days) to the variability of the *foF*2, *Ann. Geophysicae*, **16**, 168-175.

BOŠKA, J. and P. ŠAULI (2001): Observations of gravity waves of meteorological origin in the *F*-region ionosphere, *Phys. Chem. Earth (C)*, **26** (6), 425-428.

BOŠKA, J., D. BUREŠOVA and P. ŠAULI (2000): Changes of electron concentration measured by ionospheric vertical sounding in Průhonice during solar eclipse of 11.8.1999, in *EGS, ST9*, Nice, France.

BOŠKA, J., P. ŠAULI, D. ALTADILL, G. SOLÉ and L.F. ALBERCA (2003): Diurnal variation of the gravity wave activity at midlatitudes of the ionospheric *F*-region, *Studia Geophys. Geod.*, **47**, 579-586.

BOSKOVA, J. and J. LAŠTOVIČKA (2001): Seasonal variation of gravity wave activity in the lower ionosphere in Central Europe. *Studia Geophys. Geod.*, **45**, 85-92.

CHIMONAS, G. and C.O. HINES (1970): Atmospheric gravity waves induced by a solar eclipse, *J. Geophys. Res.*, **75**, 857-875.

FELTENS J., N. JAKOWSKI and C. NOLL (2001): High-Rate SolarMax IGS/GPS Campaign «HIRAC/SolarMax», *CDDIS Bulletin*, April 2001, **16** (3).

FORBES, J.M., S.E. PALO and X. ZHANG (2000): Variability of the ionosphere, *J. Atmos. Sol.-Terr. Phys.*, **62**, 685-693.

GALUSHKO, V.G., V.V. PAZNUKHOV, Y.M. YAMPOLSKI and J.C. FOSTER (1998): Incoherent scatter radar observations of AGW/TID events generated by the solar terminator, *Ann. Geophysicae*, **16**, 821-827.

HOCKE, K. and K. SCHLEGEL (1996): A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982-1995, *Ann. Geophysicae*, **14**, 917-940.

HUNSUKER, R.D. (1987): The sources of gravity waves, *Nature*, **328**, 204-205.

KAZIMIROVSKY, E.S., M. HERRAIZ and B.A. DE LA MORENA (2003): Effects on the ionosphere due to phenomena occurring below it, *Surv. Geophys.*, **24**, 139-184.

LAŠTOVIČKA, J. (2001): Effects of gravity and planetary waves on the lower ionosphere as obtained from radio wave absorption measurements, *Phys. Chem. Earth (C)*, **26**, 381-386.

LAŠTOVIČKA, J. and P. ŠAULI (1999): Are planetary wave type oscillations in the *F*2-region caused by planetary wave modulation of upward propagating tides?, *Adv. Space Res.*, **24**, 1473-1476.

LAŠTOVIČKA, J., P. KRIZAN, P. ŠAULI and D. NOVOTNA (2003a): Persistence of the planetary wave type oscillations in *f0F2* over Europe, *Ann. Geophysicae*, **21**, 1543-1552.

LAŠTOVIČKA, J., P. KRIZAN and P. ŠAULI (2003b): Persistence of the planetary wave type oscillations in *foF*2 at northern middle latitudes, in *Symp. GAII. 01, XXIII Gen. Ass. IUGG*, Sapporo, Japan.

LAŠTOVIČKA, J., P. KRIZAN and D. NOVOTNA (2003c): Persistence of planetary waves in the lower ionosphere, *Studia Geophys. Geod.*, **47**, 161-172.

LIU, J.Y., C.C. HSIAO, L.C. TSAI, C.H. LIU, F.S. KUO, H.Y. LUE and C.M. HUANG (1998): Vertical phase and group velocities of internal gravity waves derived from ionograms during the solar eclipse of 24 October 1995, *J. Atmos. Sol.-Terr. Phys.*, **60**, 1679-1686.

MENDILLO, M., H. RISBETH, R.G. ROBLE and J. WROTEN (2002): Modelling *F*2-layer seasonal trends and day-to-day variability driven by coupling with the lower atmosphere, *J. Atmos. Sol.-Terr. Phys.*, **64**, 1911-1931.

MÜLLER-WODARG, I.C.F., A.D. AYLWARD and M. LOCKWOOD (1998): Effects of a mid-latitude solar eclipse on the thermosphere and ionosphere: a modelling study, *Geophys. Res. Lett.*, **25**, 3787-3790.

PANCHEVA, D., N. MITCHELL, R.R. CLARK, J. DROBJEVA and J. LAŠTOVIČKA (2002): Variability in the height of the ionospheric *F*2-layer over Millstone Hill (September 1998-March 2000); influence from below and above, *Ann. Geophysicae*, **20**, 1807-1819.

RISHBETH, H. and M. MENDILLO (2001): Patterns of *F*2-layer variability, *J. Atmos. Sol.-Terr. Phys.*, **63**, 1661-1680.

SALBY, M.L. (1984): Survey of planetary-scale traveling waves: The state of theory and observations, *Rev. Geophys. Space Phys.*, **22** (2), 209-236.

ŠAULI, P. (2001a): Wave-like effects in the ionosphere connected with the passage of the gravity waves of tropospheric origin, *D. Thesis* (Faculty of Mathematics and Physics, Charles University of Praha, Czech Republic), (in Czech).

ŠAULI, P. (2001b): Wave-like effects in the ionosphere connected with the passage of the gravity waves of tropospheric origin, *Auto Report of D.Thesis* (Faculty of Mathematics and Physics, Charles University of Praha, Czech Republic).

ŠAULI, P. and P. ABRY (2003): Detection of the wave-like structures in the *F*-region electron concentration, in *Proceedings of 2nd Workshop COST 271*, RAL.

ŠAULI, P., and J. BOŠKA (2001): Tropospheric events and possible related gravity wave activity effects on the ionosphere, *J. Atmos. Solar Terr. Phys.*, **63**, 945-950.

ŠAULI, P., P. ABRY and J. BOŠKA (2003a): Wave structures observed in the ionospheric F-region during low and high geomagnetic activity, in *Symp. GAII. 06, IUGG*, Sapporo, Japan.

ŠAULI, P., P. ABRY, D. ALTADILL and J. BOŠKA (2003b): Height dependence of gravity wave activity in the *F*-region ionosphere, in *Symp. GAII. 06, IUGG*, Sapporo, Japan.

SOMSIKOV, V.M. (1995): On mechanisms for the formation of atmospheric irregularities in the solar terminator region, *J. Atmos. Terr. Phys.*, **57**, 75-83.