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Ionospheric and geomagnetic conditions during periods of degraded GPS position accuracy: 2. RTK events during disturbed and quiet geomagnetic conditions

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Abstract

The paper analyzes the ionospheric conditions associated with strong RTK events observed during the strong geomagnetic storm on 31 March 2001 and on 16 January 2000, a day with very low geomagnetic activity. The analysis is based on ionograms obtained from ground-based ionosondes stations at Chilton (UK), Juliusruh (Germany), and Dourbes (Belgium). The storm onset on 31 March 2001 occurs at 0058UT followed by decreasing the F layer ionization and sharp increase of its height. At sunrise, a layer, classified as F0.5, tears off the normal F layer and start descending as the time develops. It merges the normal E layer about 2 h later. The second RTK event on that day, with larger intensities, occurs in association of a series of substorms in the afternoon hours. Then ionograms clearly show the presence of side reflections, interpreted as large-scale traveling ionospheric disturbances (LSTIDs). In the quiet period 16–19 January 2000, strong RTK events are observed to appear in the morning hours and disappear in afternoon. The behavior of the bottomside ionosphere on 16 January 2000 is analyzed in details. The E layer traces first appear on ionograms at height of 150 km instead of 100 km, as it usually happens. This layer, classified as E2 layer, is accompanied in most of the cases examined with a “c” type Es layer, as they both descent to the height of the normal E layer within 2–3 h. The appearing of morning RTK events during winter months is suggested to reflect phenomena known in the literature as tidal ion layers and solar terminator associated processes.

Keywords: Middle-scale traveling ionospheric disturbances (MSTID); Real-time kinematics (RTK); Total electron content (TEC); Bottomside ion layers

1. Introduction

Real-time kinematic (RTK) is a technique based on GPS carrier phase measurements which allows to measure positions in real time with a centimeter level accuracy. GPS carrier phase measurements are ambiguous: they contain an inherent unknown integer number of cycles. Precise positioning with RTK require the resolution of this unknown integer number of cycles which is called “ambiguity”. Small-scale ionospheric plasma disturbances can strongly degrade the ambiguity resolution process and lead to errors of several decimeters in the measured positions (Seeber, 2003).

Warnant et al. (this issue) (hereafter referred as paper 1) developed a method for detecting the small-scale plasma disturbances by using continuously measured TEC from GPS signals. The method calculates the rate of change (the difference between two consecutive TEC values in TECU/min units) for each tracked satellite and approximates it with a low order polynomial in every 15 min interval. Then, the standard deviation σ_R of the residuals remaining after subtracting the polynomial (de-trended values) is computed on 15 min intervals separately for each satellite in view. When this standard deviation is larger than a threshold value (0.08 TECU/min), we decide that

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an "RTK ionospheric event" has been detected . In addition, an "RTK ionospheric intensity" (or shortly RTK intensity) is associated to each RTK ionospheric event: the intensity of the event (the amplitude of the associated TEC variations) is assessed based on a scale which ranges from 1 to 9 depending on the magnitude of σ_R (see details in paper 1). This quantity is a measure of amplitudes of the small-scale irregularity structures, effectively degrading the accuracy of the RTK positioning technique. The method is sensitive to irregularities with characteristic size of 30–60 km. The hourly RTK ionospheric intensity is obtained by making the sum of all the individual RTK intensities (corresponding to the RTK events detected during 1 h on all the satellites in view). In the same way, the hourly number of events is defined as the sum of all the events detected during 1 h for all the satellites in view. In practice, a threshold of 20 for RTK hourly intensity is accepted to define ionospheric conditions which can yield strongly degraded RTK positioning conditions (see paper 1). "Strong" RTK events will be defined as events with hourly RTK intensity values larger than 20. Warnant et al. (2006) have showed the effect of strong RTK events on RTK positioning technique. Strong RTK events are found both during geomagnetic storms and during low geomagnetic activity. They appear predominantly in morning hours (those connected with geomagnetic storms are rear) and winter months. During the last solar cycle, maximum occurrence is observed at higher solar activity.

The ionospheric irregularity structures are known to propagate away from their areas of origin, driven by atmospheric gravity waves (Hines, 1960). The moving ionospheric structures are known also as travelling ionospheric disturbances (TIDs). Various measuring techniques have revealed a great diversity of TIDs scale: from 6.1-m field-aligned irregularities detected by 25.5 MHz radar (Tsunoda et al., 1998) to over 2000 km-wavelength LSTIDs (Large-scale TIDs) detected by the GPS network over Japan (Tsugawa et al., 2004). In respect to their spectral parameters, TIDs are divided into three main groups: large-scale TIDs with a wavelength more than 1000 km and period of 0.5–3.0 h and middle-scale TIDs (MSTIDs) with a wavelength of 100–1000 km and periods 0.2–1.0 h. The other group represents the smallest scale size TIDs (SSTIDs) with a wavelength of 1–100 km and period of several minutes.

The LSTIDs are closely related to the geomagnetic storms. It is well accepted that LSTIDs are generated within the auroral oval during substorms, when large energy pulses excite atmospheric gravity waves (AGW), which then propagate equatorward with a phase speed of 300–1000 m/s (Hocke and Schlegel, 1996; Tsugawa et al., 2004). Extensive climatological study of MSTIDs by using GPS TEC measurements has been conducted by Kotake et al. (2006). They found that MSTIDs characteristics differ significantly in respect to latitude, longitude, season, and diurnal changes. MSTIDs have horizontal phase speed of 100–300 m/s and occur more frequently than LSTIDs. Their generation is not well understood, although many possible mechanisms have been proposed, such as orographic effects (Beer, 1974), wind shear (Mastrantonio et al., 1980), solar terminator (Beer, 1978; Somiskov, 1995), tropospheric effects (Bertin et al., 1978), breaking of atmospheric tides (Kelder and Spoelstra, 1987), etc. All these mechanisms do not include geomagnetic activity as a primary driver, although some non-linear interactions with LSTIDs are also assumed (Beach et al., 1997).

In the bottomside ionosphere the small-scale ionospheric disturbances are mostly seen as sporadic Es layers. Mathews, 1998 has revealed the fundamental role of diurnal and semidiurnal tides in formation of these layers, also referred as "tidal ion layers (TIL)". The midlatitude Es layers, formed by the diurnal and semidiurnal tides in the lower thermosphere through downward propagating wind shears of ion convergent nodes, are regularly seen on ionograms (Haldoupis et al., 2006). These authors found that the irregular structures descent downwards from about 130 km to the heights of the regular E layer with a speed 5–8 km/h and have twice-per-day periodicity.

Electron density in the intermediate E–F region layers is too small to affect directly TEC, or the RTK intensity. There are strong evidences that these lower ionosphere structures can be electrically connected with the F region plasma. Kelley et al. (2002) and Haldoupis et al. (2003) have suggested that enhanced polarization field set up inside the unstable sporadic-E patches may penetrate in the F region and create midlatitude spread F. Mathews et al. (2001), using high resolution ISR data from Arecibo, have detected as small as kilometer-scale layered structures inside spread F. These authors pointed out to the self-similar distribution of instability structures inside the F spread event, ranging in scale from 1 to 100 km and even extended down to characteristic scales less than 3 m. The regular nature of the disturbed plasma was pointed out by Djuth et al. (2004), who found that a continuum of gravity waves are always present in the thermosphere over Arecibo.

The present paper analyzes the appearance of strong RTK events during geomagnetic storm of 31 March 2001 and within the low geomagnetic activity period 16–19 January 2000 and associated structures in the bottomside ionosphere, seen on ionograms from ground-based ionosondes.

2. RTK events

As shown in paper 1, periods with high hourly RTK intensity values occur during strong geomagnetic storms. Fig. 1 augments such a case during the storm 31 March–1 April 2001. The geomagnetic storm starts with SSC (Sudden Storm Commencement) at 0052 UT on 31 March (0152 Central European Time – CET), followed by a sharp decrease of D_{st} to –380 nT. Further in the paper, the time is shown for UT + 1 time zone. During the initial phase, TEC decreases sharply, reaching a level 50% below its median

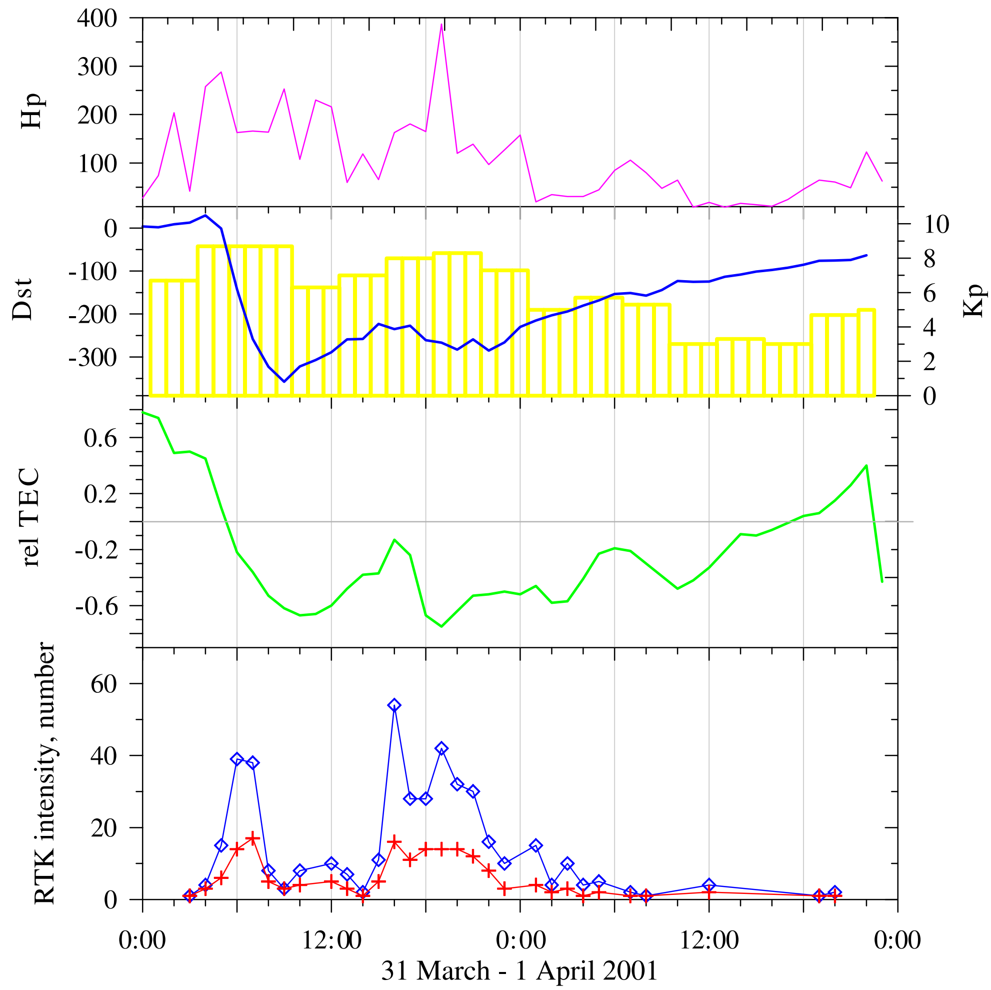

Fig. 1. RTK hourly intensity and hourly number of events during geomagnetic storm on 31 March 2001 (period 30 March–1 April 2001). The *X*-axis shows the Central European Time (CET = UT + 1). The bottom panel of Fig. 1 shows the number of RTK events (red crosses) detected per hour at Brussels reference station (BRUS) during year 2001 and the corresponding hourly RTK ionospheric intensity (blue diamonds). Both are scaled on the left. The green dots in the upper part of the panel represent hourly values of the relative deviations (rTEC), scaled on the right. The middle panel shows geomagnetic indices Dst (blue line) and Kp (yellow bars). The upper panel represents the Hemispheric Power index (Hp).

value. A series of substorms take place during the main phase of the storm. The first substorm at the time of SSC, produces a substantial auroral activity (increasing Kp to 6), but does not have effect on TEC and RTK intensity. The next substorm (onset around 03:00) seems to generate the morning strong RTK events between 05:00 and 08:00 on the background of decreasing TEC. The first elevated RTK hourly intensity at 05:00 delays with 2 h from the substorm onset. A series of substorms are observed during the main phase of the storm, so it is not clear which is responsible for the large RTK intensities, starting at 15:00 on 31 March. During that period, TEC recovers close to its median level. In the next day, 1 April, both magnetic field and TEC gradually recover to their quiet levels.

Fig. 2 presents another type of strong RTK events occurring during quiet geomagnetic conditions. The plots show the same quantities as in the previous figures during the extremely quiet period 16–19 January 2000. The appearance of strong RTK events in each of the four days is quite similar. They appear around 09:00 (almost the same local time) and disappear around noon or in the early afternoon hours.

3. Bottomside ionosphere

To check the ionospheric conditions below the F layer peak in the time of strong RTK events, we used series of ionograms from three neighboring ionosondes: Dourbes (50.1°N, 4.6°E), Chilton (51.6°N, 1.3°W), and Juliusruh (54.6°N, 13.4°E). The distance between Brussels (50.8N, 4.3E) and Chilton is around 660 km and that between Brussels and Juliusruh is more than 1000 km. But practically, the three stations have similar latitudes. The local time difference between Juliusruh and Chilton is about one hour, while Brussels stays in the middle. During the time periods considered, Juliusruh ionosonde provided ionograms every 15 min, Chilton every half hour, and Dourbes every hour. It is obvious that direct comparison of RTK events and ionogram features could not be correct. Nevertheless, we assume that the Traveling

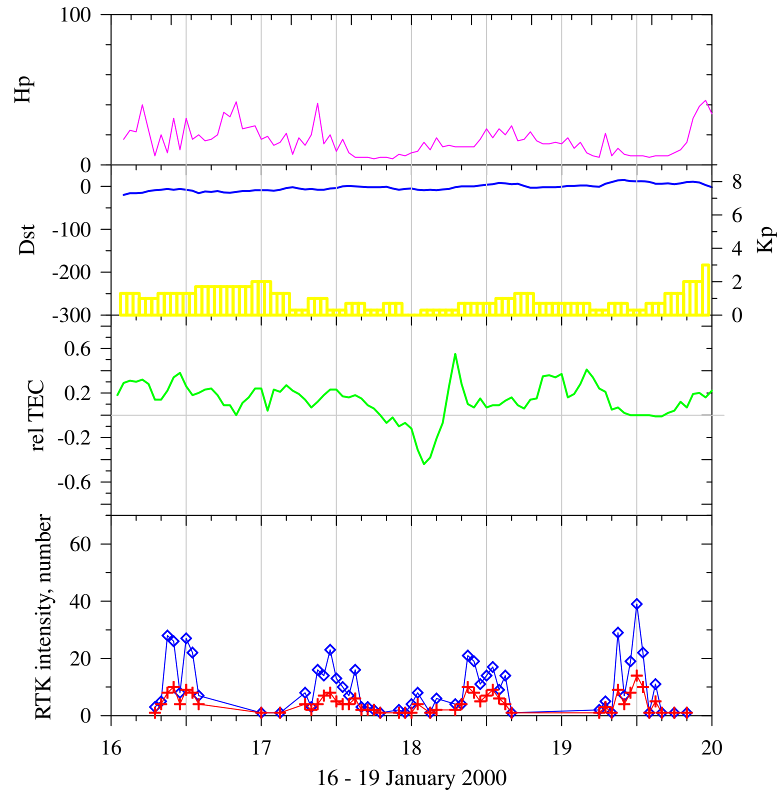

Fig. 2. The same as in Fig. 1, but for the period 16–19 January 2000.

Ionospheric Disturbances seen at Chilton and Juliusruh bring the same characteristics over Brussels after some time. For direct comparison with RTK data, the time on ionograms is changed to CET. Fig. 3 shows three series of successive ionograms from Juliusruh ionosonde along with the RTK events during the storm on 31 March 2001. For easier reference, the RTK events are shown again in the second panel. The upper row of 8 ionograms (row a) comprises the time period over the morning peak, marked as "a". The first ionogram at 05:28 shows a characteristic delay of the lower F region traces, indication of increased ionization below this height; the E layer appears at 05:43 around 120 km. At 05:58 the traces indicate the appearance of an intermediate E–F layer, classified (Piggot and Rawer, 1972) as F0.5 layer. The appearance of this layer coincides with the peak value of RTK intensity at 06:00. Further, the F0.5 layer descends and merges the normal E layer in the last ionogram at 07:13. During the whole period, traces from the normal E layer are seen on ionograms.

Rows "b" and "c" contain ionograms from the period of afternoon RTK events. The peak at 1600 corresponds to the first ionogram of row "b" at 1558, where the oblique echo at the virtual height of 600 km, indicates a presence of a TID apart from the station (Piggot and Rawer, 1972). One hour later, when the TID signature is incorporated in the F layer traces, the RTK intensity decreases. The next smaller maximum occurs at 19:00, when the ionograms show a complex structure of side reflections and spreading in both the E and F layers. These ionograms indicate the presence of localized clouds of denser plasma, probably propagating TIDs.

The ionospheric conditions during strong RTK events on 16 January 2000 are shown in Fig. 4. As seen from Fig. 2, periods with large RTK intensity values appear every morning between 09:00 and 13:00 h from 16th to 19th January 2000. In Fig. 4, fragments of successive ionograms from Chilton ionosonde show development of an intermediate E2 layer at a height of 150 km before the normal E layer appears. Chilton local time is one hour behind the time indicated on ionograms. The higher frequency part of ionograms is truncated and the traces of interest are circled. At 09:00, traces of a layer appear around 150 km, interpreted as E2 layer. In the next ionogram, a sporadic Es layer appears next to E2 trace. Both traces gradually descend to around 120 km at 10:30. A large, flat Es with critical frequency foEs of 4.9 MHz dominates at E layer heights at 11:00, partly blanketing the upper F layer traces. At 11:30, a scattered E layer seems to end the disturbed period. Next two ionograms show a quiet E layer, in coincidence with the lower value of RTK intensity at 11:00. Between 12:00 and 13:00 the RTK hourly intensity increases again, connected with a new ionospheric disturbance seen on ionograms. However, at Chilton, disturbed E layer can be followed until 14:00, while RTK intensity does not show increase after 13:00. This is probably due to localized ionospheric disturbances, having different effects at both sites.

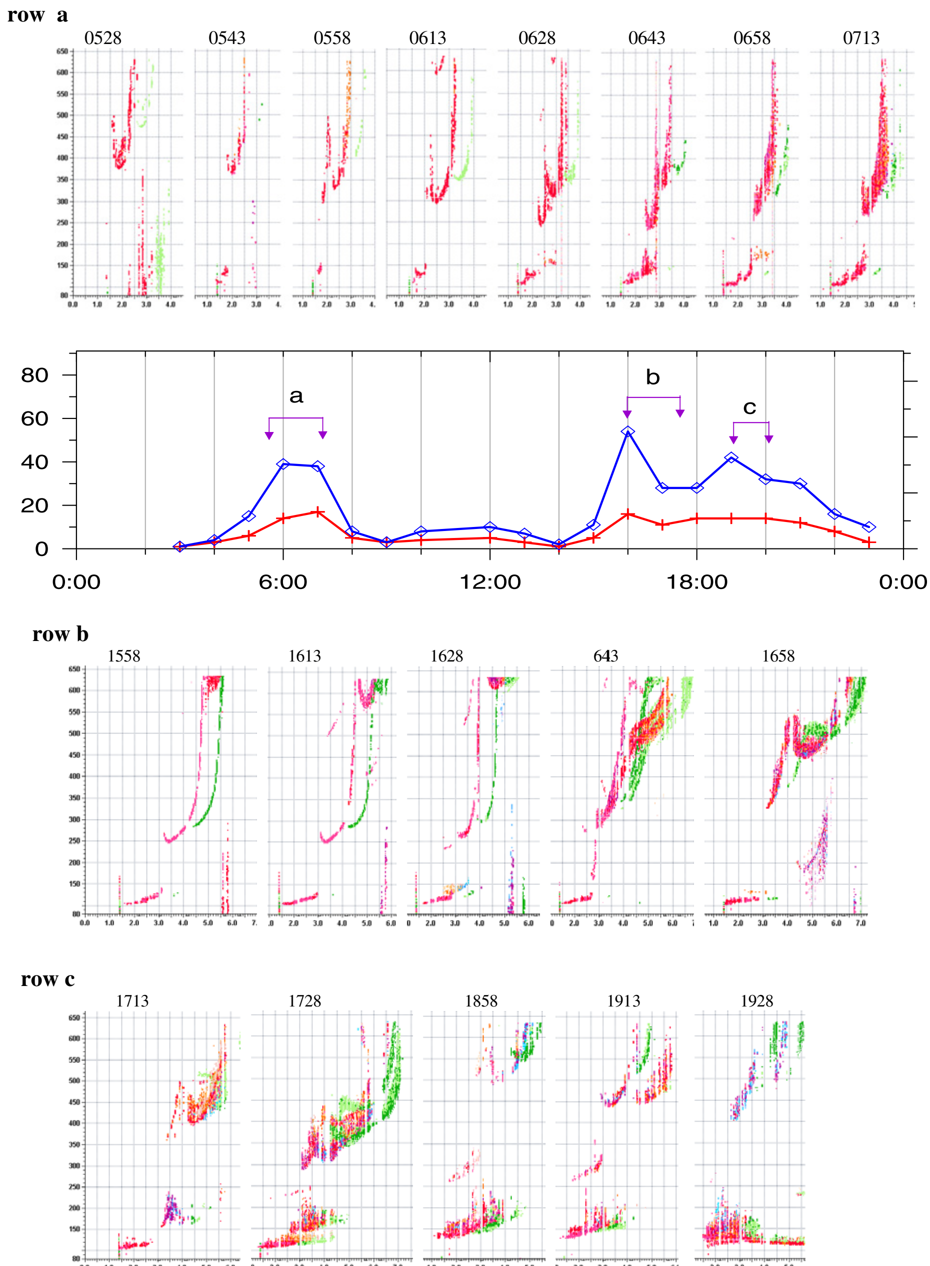

Fig. 3. Three series of successive ionograms from Juliusruh ionosonde along with the hourly RTK intensity and number of events during the storm on 31 March 2001. The ionograms in each row a, b, and c refer to the respective period, marked in the middle panel. The X-axis of each ionogram shows the sounding frequency; Y-axis at first ionogram of the row indicates the virtual height and serves to all ionograms in the row. The time (UT + 1) is given above each ionograms.

4. Discussion

The RTK intensity, described in paper 1, is a measure of small-scale disturbances. The geomagnetic storm on 31 March 2001 starts with SSC at 0158 CET followed by a series of substorms during its initial and main phase. During the initial phase of the storm the total ionization decreases steadily, with a sharp increase of the height of the F layer. The morning strong RTK events start at 05:00 and ends at 09:00. The main ionogram feature seen in row "a" of Fig. 3 is a structure, classified as F0.5 layer, which appears at lower part of the F layer and continuously descents to the E layer heights. This structure, seen first at 05:58 with a minimum virtual height of 300 km, coincides with the maximum RTK intensity. Forty-five minutes later its minimum height is 230 km. During that time, the normal E layer seems to develop in a regular way. This structure also appears in Chilton ionograms half an hour later, while at Dourbes the structure is seen as late as at 08:00. The different sounding rate of the ionosondes, however, does not allow estimating the time delay of appearance of this excessive layer over the three locations. We can speculate that

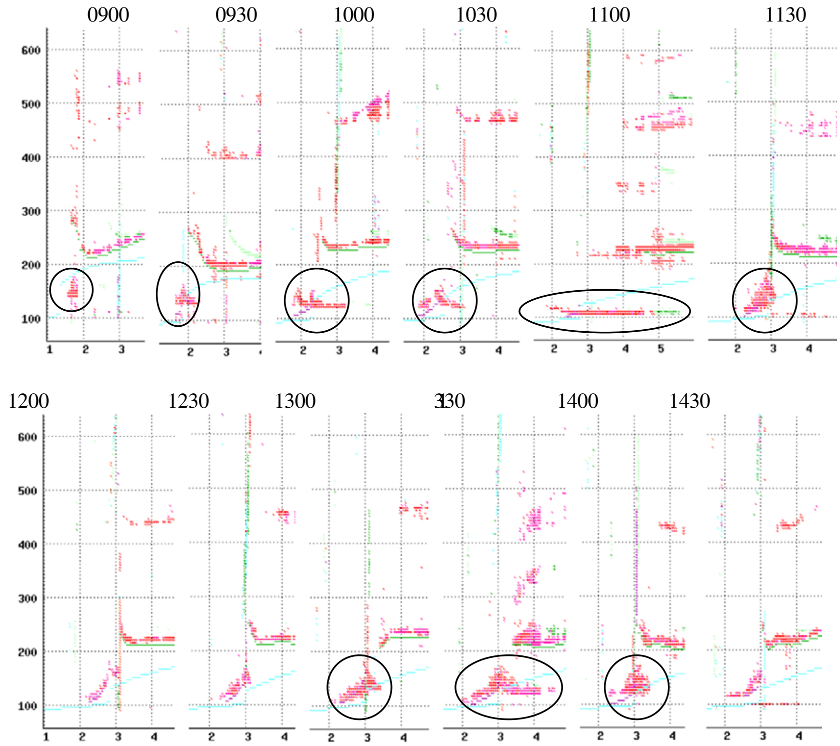

Fig. 4. Fragments of successive ionograms during the morning RTK events on 16 January 2000. The ionogram axes are the same as in Fig. 3. The traces of interest are circled.

the normal E layer is formed by photoionization, while the F0.5 layer is associated with the increased geomagnetic activity. The afternoon strong RTK events on 31 March 2001 obviously are connected with a larger-scale TID. The Digisonde sounder, operating in Juliusruh, can distinguish side reflections appearing on ionograms with different colors. This measurement feature helps interpret the oblique traces as clouds of denser or rear ionization, but cannot estimate their size. Rows "b" and "c" show that the two maximums are associated with two different ionospheric features. The row "b" shows the development of an LSTID at 1558, which 1 h later merges to the F layer traces. The row "c" represents the conditions associated with the second afternoon maximum, in which LSTIDs are not visible. Instead, an F-spread echo indicates the presence of a small-scale irregular (ripple) structure (Bowman, 1960; Mathews et al., 2001). We can conclude that both LSTIDs and spread F may produce similar effects on RTK intensity during geomagnetic storms.

In winter, RTK events frequently appear in a lack of any geomagnetic forcing. Here we show strong RTK events which occurred between 16 and 19 January 2000. As seen in Fig. 2, the RTK events appear mainly in the morning hours. The ionospheric conditions on 16 January 2000, shown in Fig. 4 do not differ substantially from the normal stage as it happened during the geomagnetic storm. The E layer traces first appear at height of 150 km instead of a layer at 100 km, as it is the case on undisturbed days. The upper layer, classified as E2 layer (Piggot and Rawer, 1972) is accompanied in most of the cases examined with a "c" type Es layer, as they both descent to the height of the normal E layer as the time develops (Haldoupis et al., 2006). Hernandez-Pajares et al. (2004) has found that these events were associated with solar terminator (ST). Indeed, ST is a stable and repeatable source of atmospheric irregularities, produced by a number of linear and non-linear mechanisms (Somiskov, 1995). Galushko et al. (1998) have used Incoherent Scatter Radar (ISR) observations at Millstone Hill to reveal the effect of ST on the generation of atmospheric gravity waves (AGWs) and TIDs. They observed strong ionospheric oscillations 2 h after sunrise (around 09:00 LT) with periods of 1.5–2 h. These oscillations propagate westwards perpendicular to ST with a group velocity of 300–400 m/s, the same speed as ST moves at ionospheric heights. Galushko et al. (1998) showed that the ST-generated low frequency disturbances, having wavelength from 100 to 1000 km, are of AGW origin. The observed by Galushko et al. (1998) disturbances in the morning hours seem similar to those shown in Fig. 2, although the spatial scale is larger than the characteristic size of RTK events. It is quite probable that the larger scale disturbances observed by Galushko et al. (1998) have internal turbulent structure, detectable by the RTK technique.

The other possible source of disturbances that can explain the appearance of morning RTK events are the tidal ion layers (Mathews et al., 1992). These layers, observed by Arecibo Incoherent Scatter Radar (ISR), usually occur at the convergent nodes of semidiurnal and diurnal tidal wind systems. The formation process of the tidal ion layers (TILs) is the so called "wind shear" mechanism

(Whitehead, 1970; Whitehead, 1989). TILs are generated at around 150 km and descent in a few hours down to 80 km. The classical intermediate TILs, generated at around 150 km are associated with the semidiurnal tide, while the lower-lying layers (known as sporadic E layers) are associated with the diurnal tide. Preferred hours for generations are 09:00 LT and midnight, although the appearance and the rate of descent can vary with seasons, geomagnetic activity and non-linear interaction with various acoustic gravity waves. TILs are regular formations, but the plasma density usually is lower than ionosondes can detect. When TIL density becomes higher (the case of interaction of tidal waves with AGWs), their traces appear in ionograms as E2 or sporadic-E layers. Mathews et al. (1992) have also found that the morning layers are more intense that the evening ones. The layer structures observed by ISR resemble the ionogram structures seen in Fig. 4. The quasi-regular nature of higher density layers agree well with the morning appearance of RTK events during 16–19 January period.

Mathews et al. (1997) have examined high-resolution ISR observations to reveal the detailed structure of TILs. They found highly irregular structure ("ion rain") associated with the wave-like TILs in the evening sector, descending from 160 km down to 100 km within 2 h. Assuming that similar process takes also place in the morning sector, it is easier to recognize the ISR descending layers with irregular structure as the RTK events.

The layer dynamics can be severely altered during geomagnetic storms. Mathews et al. (1992) found that the layers below 120 km disappeared when Kp exceeded 6. Morton and Mathews (1992) reported for such a layer disruption during the "great" magnetic storm on 13–14 March 1989. They found that the layers disappeared from the entire 80–150 km region, coinciding with sudden changes in the ground magnetogram records; the latter attributed to the generation of large electric field over Arecibo. If the ion layers/sporadic E layers are electrically coupled with the F region ionization, as Kelley et al. (2002) and Haldoupis et al. (2003) suggested, then these structures in the bottomside ionosphere can be regarded as signature of the small-scale plasma dynamics within the whole volume of ionosphere, affecting the total electron content, and can explain the observed RTK intensity phenomenon.

The processes associated with the solar terminator and the layer formation and dynamics can both explain the observed morning RTK events during disturbed and quiet geomagnetic conditions. These two phenomena do not contradict; they seem to reflect two different aspects of the complex behavior of thermosphere during the period of fast changes invoked by the moving terminator.

5. Conclusions

RTK events, which reflect the appearance of small-scale ionospheric disturbances, are associated with the appearance of disturbed structures in the bottomside ionosphere. Although, the plasma density in these disturbed structures is not high enough to affect the total electron content (TEC), the observed structures can be regarded as signature of processes comprising the whole ionosphere and especially, causing degraded GPS positioning accuracy. During the geomagnetic storm on 31 March 2001, LSTID, embedded in the daytime F layer, is the possible cause of the observed large RTK intensity. The morning RTK events are found to be associated with the intermediate E–F layers. During the geomagnetic storm, a layer, classified as F0.5, tears off the main F layer and start descending to merge the normal E layer. The spread F traces (smaller scale irregularities) are also an ionospheric signature of the RTK events. During winter months, even at quiet geomagnetic conditions, morning RTK events are frequently observed, associated with the appearance of E2 layers at around 150 km height, which also descends to the main E layer in a few hours. The morning RTK events are recognized to reflect phenomena known in the literature as tidal ion layers and solar terminator associated processes.

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