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Ionospheric and geomagnetic conditions during periods of degraded GPS position accuracy: 1. Monitoring variability in TEC which degrades the accuracy of Real-Time Kinematic GPS applications

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Abstract

The Real-Time Kinematic (RTK) positioning technique, providing centimetre-level accuracy, is most vulnerable to the ionospheric irregularities having a size comparable with the distance between the reference station and the users. In practice this distance is of order of 10–20 km. These irregularities can severely degrade the position accuracy. To monitor and study these smaller-scale ionospheric disturbances, a new method is developed, using the GPS derived TEC. The method calculates time derivatives (rate of change) from successive TEC values taken from individual satellites, de-trend their variations in 15 min intervals with low order polynomial and calculates the standard deviation from residuals. This standard deviation is a measure of amplitudes of ionospheric irregularities with characteristic period of 5–10 min and wavelength of 30–60 km. By changing the time of accumulation, the method becomes sensitive to smaller or higher scale irregularities. The standard deviation is quantified in nine grades and characterizes the level of disturbance, named RTK ionospheric intensity. The RTK ionospheric intensity above a define level is called RTK ionospheric event. It is found that the RTK ionospheric intensity has well expressed diurnal, seasonal and solar cycle occurrence. The probability of degraded positioning accuracy increases in morning hours in winter at high solar activity. It is shown that the RTK ionospheric intensity can be used as an effective tool in studying the smaller-scale ionospheric disturbances.

Keywords: Global positioning system (GPS); Traveling ionospheric disturbances (TID); Real-Time Kinematics (RTK); Total electron content (TEC)

1. Introduction

Nowadays, the Global Positioning System allows to measure positions in real time with an accuracy of a few centimetres. Such a level of accuracy can be reached after the removal or mitigation of different error sources. At the present time, the effect of the ionosphere on the propagation of GPS signals is the main factor which can strongly limit the accuracy and the reliability of high accuracy GPS applications. The correction of this effect requires an adequate modelling of the ionosphere Total Electron Content (TEC). The TEC is very variable both in space and time. It is therefore difficult to predict using simple models which can be run in real time "on the field" by Surveyors.

High accuracy real time GPS positioning techniques are usually differential techniques. It is the case of the so-called Real-Time Kinematic (RTK) technique. The principle of differential positioning is the following: a fixed reference station, of which the position is well-known, broadcasts information, called "differential corrections". These corrections improve the accuracy of a mobile user position. The closer the mobile user is with respect to the reference station, the more efficient the differential correction is. Indeed, every individual measurement made by a receiver on the

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signals emitted by a GPS satellite is affected by satellite and receiver clock errors, atmospheric (tropospheric and ionospheric) propagation delays, multipath, etc. As both the reference station and the mobile user are observing the same satellites, the RTK technique is based on the assumption that both phase measurements are affected in the same way by the different error sources (except local sources like receiver clocks and multipath). This assumption is valid as long as the separation distance between the user and the reference station remains "short enough" or in other words, as long as the error sources remain spatially correlated. To reach a-few-centimetre accuracy with RTK, the distance should not exceed 10–20 km mainly depending on spatial correlation in the ionosphere. In practice, high accuracy GPS applications are mainly affected by small-scale structures (a few km) in TEC. In particular, these structures can strongly affect or even prevent the ambiguity resolution process. Indeed, RTK uses dual frequency phase measurements made on GPS signals. By essence, phase measurements are ambiguous : there is an unknown integer number of cycles (wavelengths) inherent to phase measurements. Accurate results can only be obtained if phase ambiguities are solved, i.e., if the unknown integer number of cycles are fixed to the correct integers. On short distances, one assumes that the differential corrections broadcast by the reference station removes the ionosphere effect on phase measurements made by the mobile user. The accuracy of this ionospheric correction is usually acceptable which respect to the positioning accuracy of a few centimetres which can be expected from RTK technique. Nevertheless, when small-scale irregularities are present in the ionosphere, the mobile user phase measurements will contain residual ionospheric effects due to the gradients in TEC induced by these small-scale structures. When these residuals effects are not negligible with respect to the wavelength of GPS signals (about 20 cm), ambiguities can be fixed to a wrong integer : this problem can lead to errors of several decimetres on the RTK user position (Hofmann-Wellenhof et al., 2001). Let us mention that a gradient of 1 TECU will give a residual error of about 16 cm (on the L1 carrier) on the mobile user phase measurement. More details on the RTK positioning technique can be found in (Seeber, 2003; Hofmann-Wellenhof et al., 2001).

The ionospheric disturbances have been measured by various techniques, such as ionosondes (Bowman, 1990), HF Doppler (Waldock and Jones, 1987), satellite beacon (Evans et al., 1983), ground radars (Ogawa et al., 1994) and airglow imaging (Shiokawa et al., 2003). Comprehensive reviews on atmospheric gravity waves and mesoscale ionospheric disturbances are given by Hunsucker (1982), Whitehead (1989) and Mathews (1998). GPS derived TEC has proven to be an useful tool for studying the large- and medium-scale ionospheric disturbances. Extensive study of the medium-scale travelling ionospheric disturbances (MSTIDs) was conducted by Kotake et al. (2006), analysing short-term deviations of TEC from its hourly averaged values. The present paper focuses on shorter TEC variations and proposes a new technique for studying smaller-scale ionospheric disturbances, based on GPS signals, recorded by ground based receivers. Further in the paper we use the term "smaller-scale" for TEC variations under study, because the term "small-scale" is usually connected to those irregularities which produce scintillation effects.

As was mentioned above, the positioning provided by the RTK technique is most vulnerable to the smaller-scale plasma irregularities, having a spatial scale of few tens of km. To study these smaller scale ionospheric features, we present here a method which uses the GPS signals recorded at basic GPS receiving stations. This method is not connected directly with the RTK positioning technique, but we regard the method as serving to assess and to mitigate the degradation of the positioning accuracy. In this regard, we use the term *RTK ionospheric variability* (or shorter*RTK variability*) to that part of the ionospheric variability which affects the positioning accuracy.

GPS carrier phase measurements can be used to monitor local TEC variability. At any location, several GPS satellites can simultaneously be observed at different azimuths and elevations. Every satellite-to-receiver path allows to "scan" the ionosphere in a particular direction. The more satellites are simultaneously observed, the "denser" the information on the ionosphere is. In particular, smaller-scale ionospheric structures can be detected by monitoring TEC high frequency changes at a single station. Wanninger (1992) and Wanninger, 1994 have developed a method allowing to monitor ionospheric irregularities based on a combination of GPS dual frequency phase measurements. In particular, this method was applied to scintillation monitoring in Brazil. Warnant (1996, 1998, and 2000) further developed the method for conducting "climatological" studies on smaller-scale ionospheric activity at the mid-latitude station in Brussels, Belgium.

The present paper provides the theoretical background of the method, defines its ionospheric derivative – ionospheric variability, and outlines its general features. The output product of the method, called RTK ionospheric intensity is used to specify the ionospheric and geomagnetic conditions during the periods of degraded GPS positioning accuracy. The companion paper (Warnant et al., 2007 – hereafter denoted as paper 2) is an application of the method in studying the ionospheric smaller-scale structure. Paper 2 uses the RTK ionospheric intensity in two case studies: during an intense geomagnetic storm and at very low geomagnetic activity in order to reveal the associated ionospheric conditions.

2. Monitoring of ionospheric smaller-scale structures using GPS data

As already mentioned, TEC variability can be monitored using the geometry-free combination of dual frequency phase measurements $\Phi^{i}_{p,GF}$(Warnant and Pottiaux, 2000):

$$\Phi^i_{p,GF} = \Phi^i_{p,L1} - \frac{f_{L1}}{f_{L2}} \Phi^i_{p,L2} \tag{1}$$

If we neglect multipath effects, the combination can be rewritten in function of the slant TEC:

$$\Phi^i_{p,GF} = -0.552\ TEC^i_p + N^i_{p,GF} \tag{2}$$

with f_{L1}, f_{L2} being the frequency of the $L1$, $L2$ carriers (in Hz);

$\Phi^i_{p,L1}$, $\Phi^i_{p,L2}$ are $L1$, $L2$ carrier phase measurements (in cycles) made by receiver p on satellite i;
TEC^i_p is the slant Total Electron Content on the receiver p to satellite i path;
$N^i_{p,GF}$ is the real ambiguity (cycles).

Phase measurements usually have a precision better than one millimetre but contain an initial ambiguity which is real (non-integer) in the case of the geometry-free combination. In the absence of cycle slips, $N^i_{p,GF}$ has to be solved for every satellite pass.

From Eq. (2), it can be seen that the geometry-free combination also allows monitoring the time variation of the TEC, e.g., $\Delta TEC^i_p(t_k)$:

$$\Delta TEC^i_p(t_k) = 1.812 \frac{\left(\Phi^i_{p,GF}(t_k) - \Phi^i_{p,GF}(t_{k-1})\right)}{(t_k - t_{k-1})} \tag{3}$$

where $\Delta TEC^i_p(t_k)$, measured in TECU/min, is defined as :

$$\Delta TEC^i_p(t_k) = \frac{TEC^i_p(t_k) - TEC^i_p(t_{k-1})}{(t_k - t_{k-1})} \tag{4}$$

It is important to stress that the computation of $\Delta TEC^i_p(t_k)$ does not require the estimation of the real ambiguity, $N^i_{p,GF}$, as long as no cycle slip occurs. Eq. (3) can be used to detect high frequency changes in the TEC due to irregular smaller-scale ionospheric phenomena which can strongly affect RTK accuracy. Fig. 1 shows a sample of ΔTEC (red crosses) calculated by using all GPS satellites tracked at Brussels receiving station on 3 February 2002. The red crosses are seen grouped in clusters, each one representing the data from a single GPS satellite. The time derivation at different elevations when tracking a satellite, introduces an artificial trend, not connected with the ionospheric variability, but due to the geometry of the satellite orbit.

In order to remove the trend, we filter out the low frequency changes in the TEC by modelling ΔTEC^i_p using a low order polynomial. The residuals of this adjustment (i.e., ΔTEC^i_p- polynomial) contain the higher frequency terms. Then, the standard deviation of the residuals, σ_R, is computed, separately for every satellite in view, on 15 min periods. When $\sigma_R > 0.08$ TECU/min (on a 15 min period), we decide that an *RTK ionospheric event* is detected. The threshold value of 0.08 TECU/min has been chosen in such a way that multipath effects cannot be interpreted as ionospheric variability. Indeed, multipath is the only other error source which could be the origin of high frequency changes in the geometric free combination. In addition, an *RTK ionospheric intensity* is associated to every 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 (Table 1). Further in the paper, for sake of easy reading, we omit the term "ionospheric" to the defined variability, event and intensity, but it should be kept in mind that they refer only to ionospheric part of RTK degradation. The present analysis does not include the existing non-ionospheric effects degrading the RTK performance. All the details concerning this technique (including the choice of the thresholds) are discussed in Warnant (1998) and Warnant and Pottiaux, 2000).

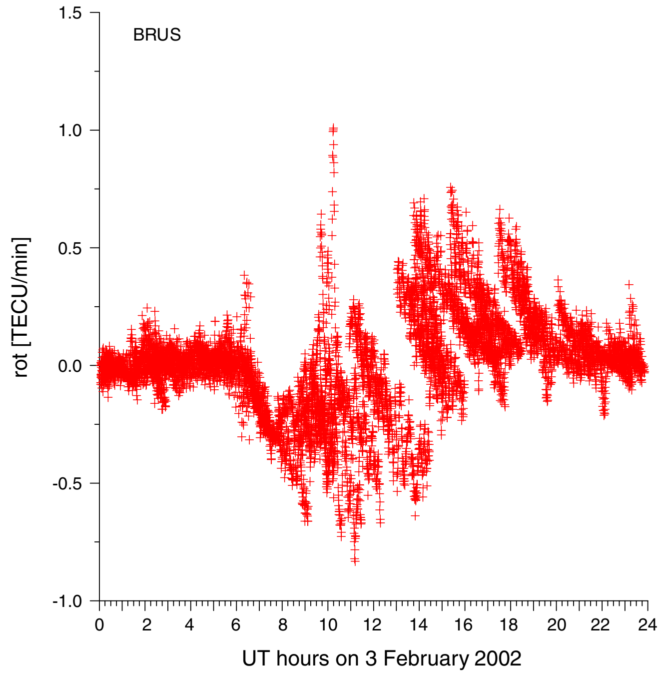

Fig. 1. Sample of ΔTEC calculated by using all GPS satellites tracked at Brussels receiving station on 3 February 2002. The red crosses are seen grouped in clusters, each one representing the data from a single GPS satellite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

Table 1
Definition of the RTK ionospheric intensity

RTK intensity	σ_R (TECU/min)
1	$0.08 \leqslant \sigma_R < 0.10$
2	$0.10 \leqslant \sigma_R < 0.15$
3	$0.15 \leqslant \sigma_R < 0.20$
4	$0.20 \leqslant \sigma_R < 0.25$
5	$0.25 \leqslant \sigma_R < 0.30$
6	$0.30 \leqslant \sigma_R < 0.35$
7	$0.35 \leqslant \sigma_R < 0.40$
8	$0.40 \leqslant \sigma_R < 0.45$
9	$\sigma_R > 0.45$

3. RTK event occurrence

The data collected in the permanent GPS station of Brussels have been used to make statistics about the frequency of occurrence of RTK events. Fig. 2 shows the number of detected RTK events per month from April 1993 to May 2006. The solar cycle dependence is well expressed. Although the database compasses only one solar cycle it is evident that RTK events predominantly happen at solar maximum.

To reveal the correlation of RTK events with geomagnetic activity, three indices: Dst, Kp and hemispheric power (Hp) are used. Dst traditionally defines the geomagnetic storm and its time development: initial, main and recovery phases. Dst variations have a time scale of one to few days. Hp, issued by the Space Environment Center, NOAA, Boulder, Colorado, is based on energetic particle measurements from satellites and highly correlates with the auroral AE index. Hp reflects the substorm activity in the auroral oval with a time scale of hours. Kp has an intermediate time scale and also defines geomagnetic activity in the auroral oval. The autocorrelation function of Kp has a time constant of about 20 h and is known to correlate best with the large scale negative ionospheric disturbances during the main phase of geomagnetic storms (Kutiev and Muhtarov, 2001). Fig. 3 shows the RTK ionospheric intensity along with geomagnetic indices during the whole year 2001.

The bottom panel of Fig. 3 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). The hourly RTK ionospheric intensity is obtained by making the sum of all the individual RTK intensities (corresponding to all the detected RTK events during one hour). Both are scaled on the left. The green dots in the upper part of the panel represent hourly values of the relative deviations (rTEC) of measured TEC from its 27-day medians. rTEC is scaled on the right.

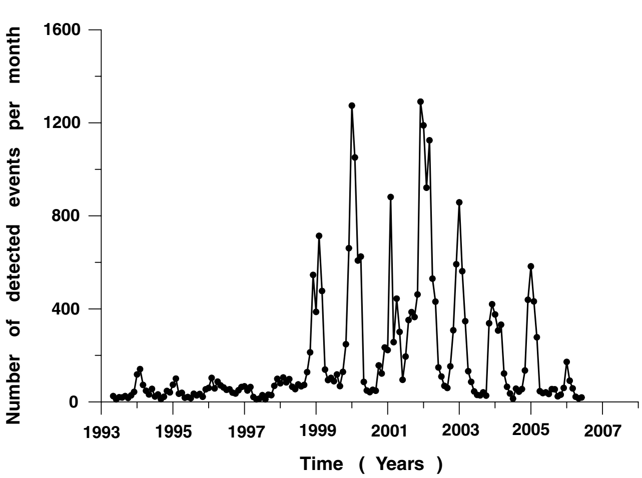

Fig. 2. Number of detected RTK ionospheric events per month at Brussels from April 1993 to May 2006.

rTEC shows the large scale ionospheric disturbances over the Belgian territory. The middle panel shows geomagnetic indices Dst (blue line) and Kp (yellow bars). The upper panel represents the hemispheric power index (Hp). During the year 2001, the most intense geomagnetic storms occurred in March–April and September–October months. Large peaks of RTK intensity are seen to occur in coincidence with the negative peaks of Dst. It is seen also, that RTK events occur outside geomagnetic storms, predominantly in winter months. Occurrence statistics is shown in Fig. 4.

In practice, a threshold of 20 for RTK intensity is accepted to define ionospheric conditions which can yield strongly degraded RTK positioning. Fig. 4a shows that the RTK > 20 occurs mainly daytime, with a well pronounced maximum in the morning hours. Fig. 4b reveals the predominant occurrence of RTK > 20 during winter months.

4. Discussion and conclusions

The present paper describes a new method for studying the appearance of smaller-scale ionospheric disturbances capable to degrade the GPS positioning accuracy. We regard this method functionally connected to the RTK positioning technique and in this sense we added the term RTK to the method output products. The method is simple enough to be widely used in studying the smaller-scale irregular ionospheric structures. Indeed, the standard deviation of TEC rate of change around the average trend, taken in a narrow time interval, is a good measure of the irregular structure. The shorter is the time interval, the smaller size irregularities are present. When the irregularities are traveling with a certain speed, they are regarded as wave-like structures with a certain periods. If the period exceeds considered time interval, the low order polynomial, which approximates the trend, will take the wave structure as part of the trend and therefore will smooth out its amplitude. Fig. 1 shows a large-scale disturbance taking place during the whole day of 3 February 2002. The traces from individual satellites involve orbit geometry trends, which are to be de-trended by low order polynomials. It is easy to see that after de-trending, only small-size irregularities (in figure look like a scatter) will contribute to the standard deviation around the trends. After extensive testing, we have chosen the 15 min time interval as a compromise between statistical sufficiency of the data and the size of detected irregularities. Roughly, the average (most likely) period of the captured disturbances is estimated at 5–10 min. The number of successive events gives the time period when the disturbances take place. This estimate is in agreement with the results shown by Hernandez-Pajares et al. (2005), ranging between 10 and 20 min for high solar activity. These authors conducted a spectral analysis on their data and found that the method they used is sensitive to the ionospheric disturbances having a spatial size of 50–150 km.

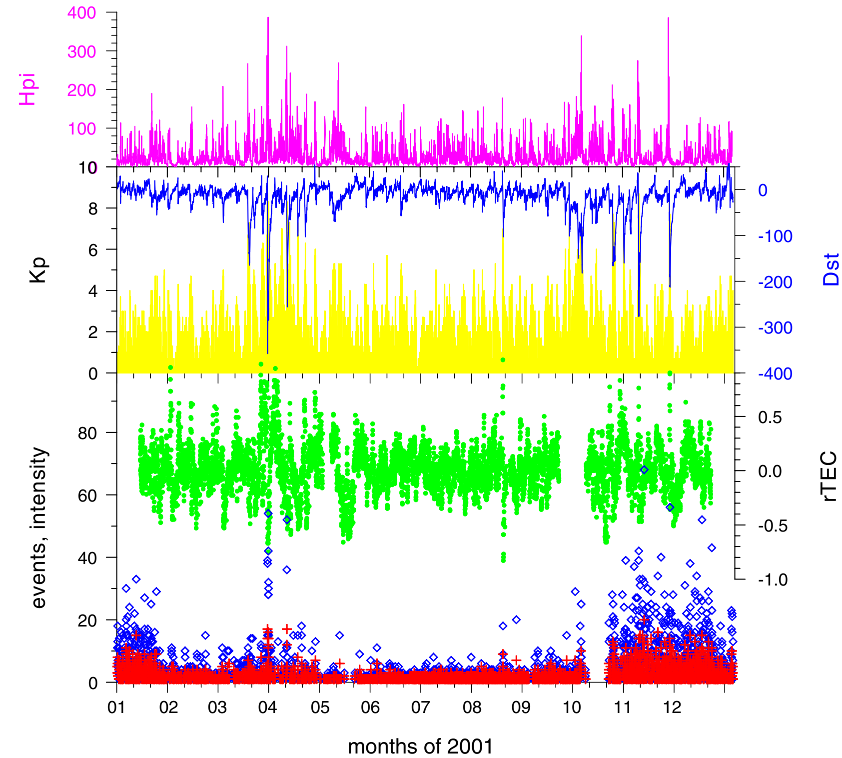

Fig. 3. RTK intensity and number of events during Year 2001. The bottom panel shows the number of RTK events (red crosses) detected per hour at Brussels reference station (BRUS) during year 2001 and the corresponding hourly RTK ionospheric intensity (blue diamonds). Both are scaled on the left. The green 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

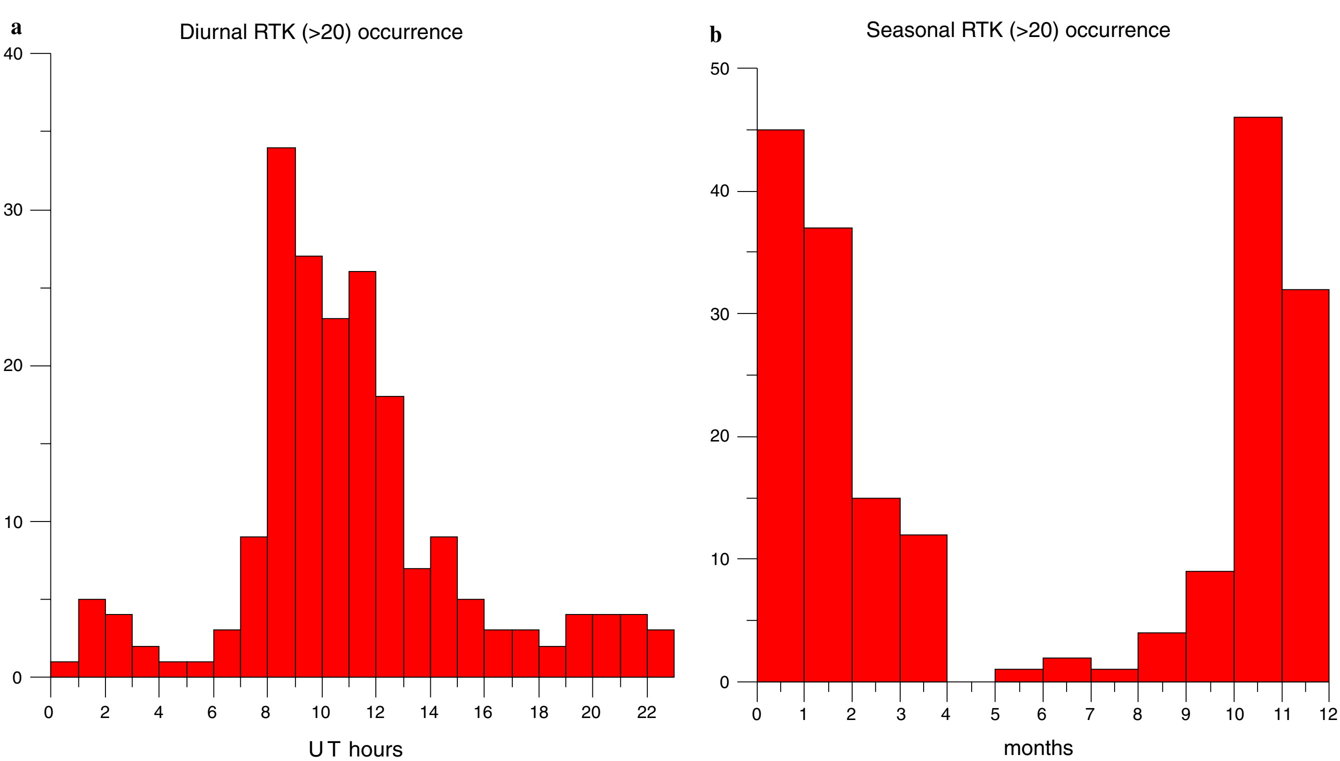

Fig. 4. Histograms of RTK intensity > 20 collected in 2000–2002. (a) Diurnal occurrence, (b) seasonal occurrence.

They found also that these irregularities are traveling with an average velocity of 100–300 m/s towards south-east in winter and north-west in summer. However, these authors pointed out that the upper limit of real wavelengths range should be larger, from 50 to 300 km.

As seen from Fig. 3, RTK events with higher intensity well correlate with geomagnetic storms. Although a detailed correlation analysis has not been made, it is evident that the largest RTK intensities are associated with the main phases of the storms. In winter, however, most RTK events with small or moderate intensity may appear during prolonged period of low geomagnetic activity. The paper 2 analyzes these features in detail. During geomagnetic storms, large-scale TIDs embedded in the daytime F layer, are assumed as a possible cause of the observed high RTK intensity. 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 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.

The statistical occurrence on Fig. 4 shows that the RTK events predominantly occur in the morning hours and winter months. This finding is not supported by the works based on airglow images (Garcia et al., 2000; Shiokawa et al., 2003). The reason is that airglow is observed only nighttime, while our statistics shows that RTK event happen mostly during daytime. However, MSTIDs, extracted by the airglow images show larger periods and wavelengths than the present method provides. Shiokawa et al. (2003) reported for typical wavelength of 100–300 km, velocity of 50–100 m/s and periods of 0.5–1.5 h. Obviously, RTK variability represents the smaller size part of irregularity spectrum. If we suppose that irregularities of the whole spectrum are traveling with the same speed, a typical velocity of 100 m/s will convert our periods of 5–10 min to an wavelength of 30–60 km. Irregularities of this size, as seen from RTK technique definition, could effectively degrade the GPS positioning accuracy.

In conclusion, a new method for detecting the smaller-scale ionospheric irregularities is developed by using GPS carrier phase measurements. The irregular structures of this size affect the GPS positioning provided by the RTK technique and degrade its accuracy. At the same time the simplicity of the method and the large database accumulated allows conducting extensive studies on the physical nature of the smaller size irregularities.

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