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A novel method for the quantitative assessment of the ionosphere effect on high accuracy GNSS applications, which require ambiguity resolution

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Abstract

Real time kinematic, or RTK, is a high-accuracy GPS relative positioning technique, which allows to measure positions in real time with an accuracy usually better than 1 decimeter. Ionospheric small-scale variability can strongly degrade RTK accuracy. In this paper, we present a method allowing to assess in a direct quantitative way the influence of the ionospheric activity on RTK accuracy. We apply this method to two different ionospheric situations: a day where strong travelling ionospheric disturbances (TIDs) were detected (December 24, 2004) and a day where a severe geomagnetic storm was observed (November 20, 2003). We show that on a 4 km baseline, strong TIDs have the same influence as the ionospheric variability induced by a geomagnetic storm on RTK accuracy: in both cases errors of more than 1.5 m are observed.

Keywords: Ionosphere; TIDs; GPS; GNSS; Geomagnetic storm; RTK

1. Introduction

Nowadays, Global Navigation Satellite Systems, or GNSS, allow to measure positions in real time with an accuracy ranging from a few metres to a few centimetres mainly depending on the type of observable (code or phase measurements) and on the positioning mode used (absolute, differential or relative). In absolute mode, the observer measures his absolute position with only one receiver; the differential mode is a particular case of the absolute mode: the observer still wants to measure his absolute position with only one receiver but he makes use of differential corrections broadcast by a reference station. These corrections allow to improve the quality of the measured positions. In relative mode, the observer combines the measurements collected by at least two receivers. The absolute position of one of these two receivers (called reference receiver or reference station) must be known. Based on the combined measurements, it is possible to compute the vector (often called baseline) between the two receivers. Then, the absolute position of the second receiver can be obtained.

The best accuracies can be reached in differential or relative mode using phase measurements. For example, the so-called Real Time Kinematic (RTK)

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technique allows to measure positions in real time with an accuracy usually better than a decimetre. RTK can be used in both differential and relative mode. The level of accuracy obtained mainly depends on the distance between the reference station and the mobile user of whom the position is unknown. Indeed, the RTK technique makes the assumption that the phase measurements made at the reference station and by the mobile user are affected in the same way by most of the error sources: satellite clock and orbit errors, atmospheric effects. In practice, the distance between the reference station and the user is usually smaller than 20 km.

At the present time, ionospheric effects remain the most important error source in high-accuracy positioning with the RTK technique. In particular, smaller-scale variability in the ionospheric plasma can be the origin of strong degradations of RTK accuracy (Seeber, 2003). In the past, many studies have been dedicated to ionospheric effects on real time positioning techniques. Most of them aimed at developing mitigation techniques which allow to improve the precision obtained on short distances (see for example Wanninger, 1999; Ou and Wang, 2004) or aimed at increasing the "acceptable" distance between the stations considered while minimising the errors (see for example, Chen et al., 2004; Hernandez-Pajares et al., 2000). In our paper, we develop a method allowing to assess the residual ionospheric error which remains when the mitigation techniques fail to removed the effects. The method developed in the frame of this article, does not aim at improving the precision obtained in RTK positioning but it allows to monitor and to quantify the contribution of ionospheric disturbances to the RTK technique error budget.

2. Principle of the RTK technique

As already stated, the RTK technique can be run either in differential or in relative mode. To fix ideas, we choose to discuss ionospheric effects on RTK used in relative mode: ionospheric disturbances have the same influence on both positioning modes.

In relative mode, RTK users combine their own phase measurements with the measurements made by a reference station of which the position is precisely known. In practice, the mobile user forms double differences between his own phase measurements and the phase measurements collected in the reference station. In this paper, we call receiver A, the reference station receiver, and receiver B, the user receiver.

If we neglect multipath effects, the simplified mathematical model of phase measurements made by receiver A on satellite i, φ_A^i (in cycles) can be written as follows (Seeber, 2003; Leick, 2004):

$$\varphi_A^i = \frac{f}{c}\left(D_A^i + T_A^i - I_A^i + c\left(\Delta t^i - \Delta t_A\right)\right) + N_A^i, \tag{1}$$

where D_A^i is the geometric distance between receiver A and satellite i; I_A^i the ionospheric error; T_A^i the tropospheric error; Δt_A the receiver clock error (the synchronisation error of the receiver time scale with respect to GPS time scale); Δt^i the satellite clock synchronisation error (the synchronisation error of the satellite time scale with respect to GPS time scale); N_A^i the phase ambiguity (integer number); and f the considered carrier frequency (L1 or L2).

If we neglected higher-order terms (terms in f^{-3}, f^{-4},), the ionospheric error I_A^i is given by

$$I_A^i = 40.3\frac{TEC_A^i}{f^2}, \tag{2}$$

where TEC_A^i is the slant TEC from satellite i to receiver A (in electron/m^2).

If φ_A^i and φ_B^i are phase measurements made simultaneously by receivers A and B on satellite i, the single difference φ_{AB}^i is defined as

$$\varphi_{AB}^i = \varphi_A^i - \varphi_B^i. \tag{3}$$

If receivers A and B observe a second common satellite j, we can form a second single difference. Then, the double difference φ_{AB}^{ij} is defined as

$$\varphi_{AB}^{ij} = \varphi_{AB}^i - \varphi_{AB}^j. \tag{4}$$

Based on Eq. (1), Eq. (4) can be rewritten:

$$\varphi_{AB}^{ij} = \frac{f}{c}\left(D_{AB}^{ij} + T_{AB}^{ij} - I_{AB}^{ij}\right) + N_{AB}^{ij}, \tag{5}$$

with the notation:

$$*_{AB}^{ij} = (*_A^i - *_B^i) - (*_A^j - *_B^j). \tag{6}$$

In the double differences, all the error sources which are common to the phase measurements performed by receivers A and B cancel, in particular, satellite and receiver clock errors. In addition, in the case of RTK, which is used on short distances, orbit residual errors can be neglected (Seeber, 2003). Residuals atmospheric effects T_{AB}^{ij} and I_{AB}^{ij} depend on the distance between A and B and also on the atmospheric "activity". Given the short distances considered, RTK data-processing algorithms assume that residual atmospheric errors are negligible. In this case, Eq. (5) can be rewritten:

$$\varphi^{ij}_{AB} = \frac{f}{c} D^{ij}_{AB} + N^{ij}_{AB}. \tag{7}$$

In RTK, the position of the reference station (station A) is known by the mobile user (station B). For this reason, the only unknowns which remain in Eq. (7) are the mobile user coordinates X_B, Y_B, Z_B (contained in the term D^{ij}_{AB}) and the ambiguity N^{ij}_{AB} which is an integer number. Let us assume that five (common) satellites (satellites 1–5) are observed in stations A and B: four independent double differences can be formed φ^{12}_{AB}, φ^{13}_{AB}, φ^{14}_{AB}, φ^{15}_{AB}. These four equations contain seven unknowns: X_B, Y_B, Z_B, N^{12}_{AB}, N^{13}_{AB}, N^{14}_{AB}, N^{15}_{AB}. Therefore, it is not possible to solve all the unknowns using only one observation epoch: RTK needs an initialisation phase. During the initialisation phase, the user remains at the same position during a few minutes so that redundant observation and sufficient information is available to solve (by least squares) the linearised double difference observations for the ambiguities and for the user position. Precise positioning with RTK requires the resolution of the ambiguities N^{ij}_{AB} to the correct integer in real-time. The ambiguity resolution requires the use of sophisticated techniques like the so-called lambda method (Joosten and Tiberius, 2000). When ambiguities are solved, the user can start to measure precise positions. Eq. (7) remains a valid mathematical model for double differences as long as residual atmospheric errors remain negligible with respect to GPS carriers wavelength (about 20 cm). This assumption is verified in usual conditions (Leick, 2004). Tropospheric residual errors are usually negligible. Nevertheless, disturbed Space Weather conditions can be the origin of smaller-scale (a few kilometres) variability in the Total Electron Content which can itself strongly degrade or even prevent ambiguity resolution due to the fact that, in that case, the mathematical model given by Eq. (7) do not adequately represent the observed double differences.

3. Ionospheric variability which affects RTK

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, 2000) further developed the method for conducting "climatological" studies on smaller-scale ionospheric activity at the mid-latitude station of Brussels, Belgium.

This method has been applied to the continuous measurements collected at Brussels since April 1993. From this study, it appears that TEC smaller-scale variability is mainly related to three types of phenomena: travelling ionospheric disturbances (TIDs), scintillations or "noise-like" variability. TIDs appear as waves in the electron density, which are due to interactions between the ionosphere and the neutral atmosphere. Fig. 1 shows the ionospheric variability due to a TID detected at Brussels on DOY 359 in 2004 (December 24, 2004). Scintillations are fluctuations in phase and amplitude of GPS signals, which are due to the presence

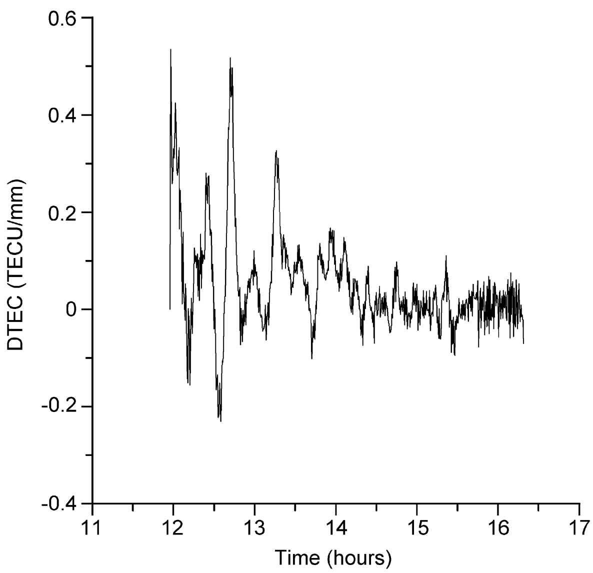

Fig. 1. TEC variability (TECU/min) due to a TID detected at Brussels on DOY 359 in 2004 along the track of satellite 21.

of small-scale irregularities in the electron concentration. Scintillations are mainly observed in the polar and in the equatorial ionosphere (Seeber, 2003). In mid-latitude stations, "noise-like" variability in TEC can also be observed. Such a variability is mainly detected during geomagnetic storms; Fig. 2 shows noise-like variability in TEC due to a severe geomagnetic storm observed at Brussels on DOY 324 in 2003 (November 20, 2003).

Warnant et al. (2006-1) and Warnant et al. (2006-2) analyse in detail the ionospheric and geomagnetic conditions under which such a variability appears mainly based on ionograms, GPS–TEC and geomagnetic measurements. In this paper, we analyse the influence of the TEC variability on RTK.

The technique developed at ROB allows to detect ionospheric smaller-scale variability based on one-way phase measurements i.e. phase measurements made by one receiver on the signal coming from one satellite (Warnant and Pottiaux, 2000). In practice, the "basic" observable used in RTK is the double difference, which depends on differential ionospheric effects. These differential effects depend on baseline length and on the scale of the ionospheric structure. Therefore, when an ionospheric disturbance is detected using the ROB one-station technique, it is very difficult to foresee the influence of this disturbance on RTK accuracy.

The impact of ionospheric small-scale variability on differenced phase observation can be analysed

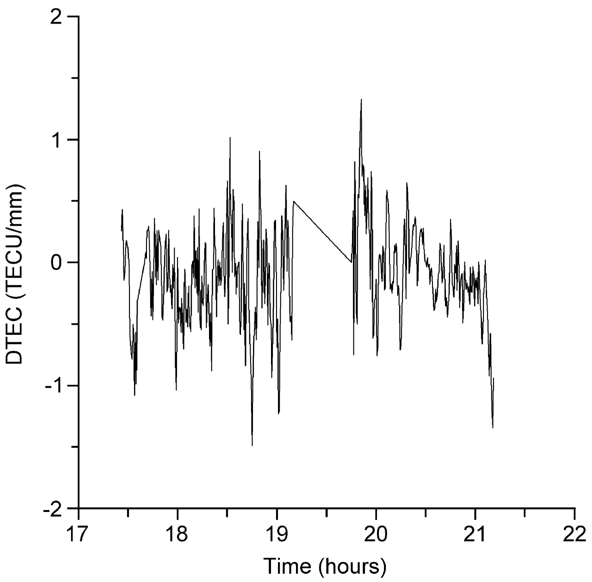

Fig. 2. TEC noise-like variability observed at Brussels on DOY 324 in 2003 along the track of satellite 15.

using the so-called geometric free combination $\varphi^i_{A,GF}$:

$$\varphi^i_{A,GF} = \varphi^i_{A,L1} - \frac{f_{L1}}{f_{L2}}\varphi^i_{A,L2}, \tag{8}$$

where f_{L1}, f_{L2}, respectively, are the L1, L2 carrier frequencies; $\varphi^i_{A,L1}\varphi^i_{A,L2}$, respectively, the L1, L2 carrier phase measurements made by receiver A on the signals emitted by satellite i.

Based on Eqs. (1) and (2), Eq. (8) can be rewritten in function of the slant TEC from receiver A to satellite i, TEC^i_A (Warnant and Pottiaux, 2000):

$$\varphi^i_{A,GF} = 0.552 \times 10^{-16}\, TEC^i_A + N^i_{A,GF}, \tag{9}$$

and $N^i_{A,GF}$, the geometric free (real) ambiguity:

$$N^i_{A,GF} = N^i_{A,L1} - \frac{f_{L1}}{f_{L2}}N^i_{A,L2}, \tag{10}$$

with $N^i_{A,L1}$, $N^i_{A,L2}$, respectively, the L1, L2 integer ambiguities.

This combination is called "geometric free" due to the fact that it does not contain geometric terms (i.e. satellite and receiver coordinates). Therefore, it cannot be used to compute the user position.

By forming double differences of the geometric-free combination, it is possible to measure the (ambiguous) differential ionospheric effect:

$$\varphi^{ij}_{AB,GF} = 0.552 \times 10^{-16}\, TEC^{ij}_{AB} + N^{ij}_{AB,GF}. \tag{11}$$

Eq. (11) uses the notation defined in Eq. (6). Even if this combination is ambiguous, it allows to monitor differential TEC changes (since the first epoch of observation) due to the presence of ionospheric disturbances.

Nevertheless, from this combination only, it is not possible to have a quantitative assessment of the RTK positioning error: in paragraph II, we explained that the RTK position is obtained from a least-squares process. This least-squares process uses double differences formed on all the common satellites in view. It is not possible to predict how the individual ionospheric residual effects affecting the double differences will be "combined" in the least-squares process and which influence it will have on the RTK final position (Warnant et al., 2007).

4. Development of an RTK accuracy monitoring software

In order to have a realistic quantitative assessment of the ionospheric influence on RTK accuracy,

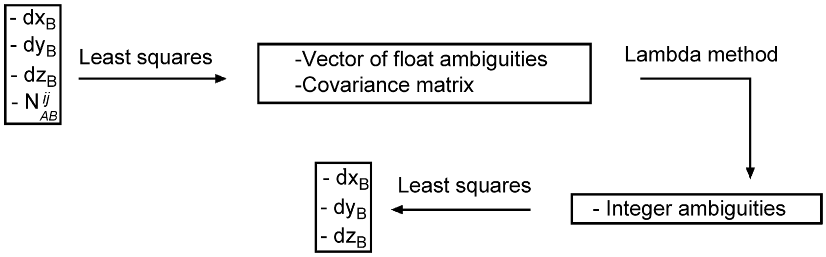

Fig. 3. Algorithm of our RTK simulation software

we decided to develop a simulation software which is similar to the software used by RTK users. The idea is to simulate the real conditions that RTK users undergo on the field. This software uses GPS permanent station data to simulate the reference station (station A) and the mobile station (station B). The position of these stations is known at a few mm level. As the "nominal" RTK accuracy is a few cm, we will consider that the position of these permanent stations is perfectly known and we will refer to it as the "true" station position.

In our technique, data are processed in four steps. In a first step, our software forms double differences based on the measurements collected on all the satellites in view in stations A and B. The observations are accumulated during 5-min periods to simulate the initialisation phase which is necessary in order to solve ambiguities to the correct integer number (see paragraph II).

In a second step, the accumulated (linearised) double difference observations are solved for the (static) user position and for the ambiguities using a least-squares process based on Eq. (7). The "true" station B position is used as a priori value in the least-squares process. At this step, ambiguities cannot be directly solved as integer numbers: mainly due to the remaining unmodelled errors (ionosphere, troposphere, multipath, measurement noise) affecting the double differences, the least-squares process outputs real numbers (called float ambiguities).

In a third step, ambiguities are solved to the most probable integer (in the least-squares sense) using the so-called lambda method. This method takes the float ambiguities and their variance–covariance matrix as input and it outputs the integer ambiguities. More details on the method can be found in Joosten and Tiberius (2000). Let us highlight the fact that ambiguities cannot be solved just by rounding off the float ambiguities to the nearest integer.

In a fourth step, the solved ambiguities are introduced as known parameter in the double differences, which are again solved for the user position, which is the only remaining unknown. The most precise results can only be reached when ambiguities are solved to the correct integer. As GPS signal wavelength is about 20 cm, it appears very clearly that incorrectly solved ambiguities (wrong integer number) will strongly affect the computed user position.

Fig. 3 summarizes the different steps of our processing technique; the unknowns contained in the linearised double differences are station B position and the ambiguities. These double differences are accumulated during 5-min periods and are solved for the unknowns using a least-squares process which provides float ambiguities and their associated variance–covariance matrix as output; these parameters are used as input for the lambda method which gives as output the most probable integer values for the ambiguities (in the least-squares sense). Then, the original double differences are "corrected" for the integer ambiguities and are solved for station B position unknowns (which are the only remaining unknowns).

As our simulation software uses data from permanent GPS stations of which the position is precisely known, we can compare the computed station B position with the true position. This comparison allows to have a direct quantitative assessment of the ionosphere influence on the accuracy of the RTK positions.

5. Results

In this paragraph, we use our simulation software to assess the influence of small-scale variability in TEC on RTK accuracy. We will analyse the degradation of RTK positioning due to TIDs, on the one hand and due to a severe geomagnetic storm, on the other hand. The results of our study are based on the data coming from the (Belgian) Active Geodetic Network, which is composed of 61 permanent GPS stations. The role of this network is to play the role of reference for real time GPS positioning applications in Belgium. In the Active Geodetic Network, station positions are known at a few millimetre level; baseline lengths range from 4 km to about 25 km.

As already explained, RTK can be used on distances up to 20 km and the influence of atmospheric (ionospheric and tropospheric) residual errors increases with the distance between the reference station and the mobile user. We choose to base our analysis on the stations Brussels and Saint-Gilles, which are separated by a distance of about 4 km. On such a short distance, we can expect only a very small contribution of the troposphere to the positioning error; therefore, in that case, except problems in satellite geometry (too few common satellites in view), only ionospheric effects can affect ambiguity resolution in a significant way.

On December 24, 2004 (DOY 359 in 2004), from 0h00 to 5h00, the ROB one-station software for the detection of ionospheric variability did not detect any event: TEC variability was very low ($\leqslant \pm 0.15$ TECU/min). Fig. 4 shows the double difference of the geometric-free combination for satellite pair 28–27 between 3h00 and 5h00 UT. Let us recall that this combination is a measure of the differential ionospheric variability with time: as expected during a period of quiet ionospheric variability, this combination remains close to a constant. Fig. 5 shows the double difference of the L1 phase observation (for the same satellite pair and for the same period), which has been corrected for the a priori value of the distance term $D^{ij}_{A\,B}$. This a priori distance term can be computed using satellite orbit information and stations A and B coordinates (our software takes the true station B coordinates as a priori value). From Eq. (7), it comes:

$$\varphi^{ij}_{AB} - \frac{f}{c} D^{ij}_{AB} = N^{ij}_{AB}. \tag{12}$$

In other words, if Eq. (7) is valid (i.e. if the residual errors remain negligible), the L1 double difference corrected for the distance term should remain close to an integer constant. This is clearly the case in Fig. 5.

Fig. 6 shows the output of our RTK simulation software. As already mentioned, this software outputs the three components (X_B, Y_B, Z_B) of the user position. To fix ideas, we choose to show the X

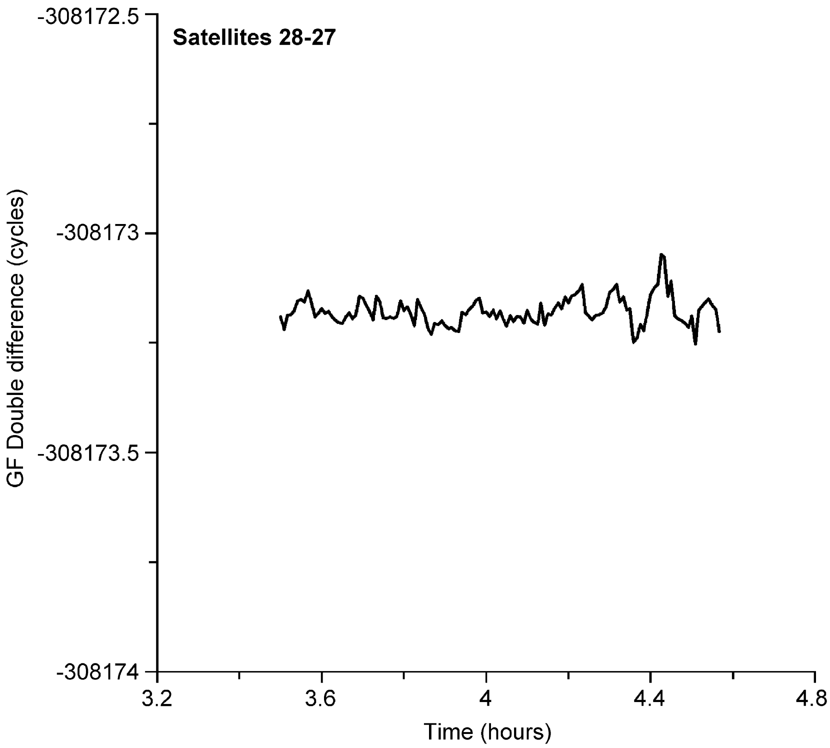

Fig. 4. Double difference of the geometric free combination on DOY 359 in 2004, baseline Brussels–Saint-Gilles, satellite pair 28-27.

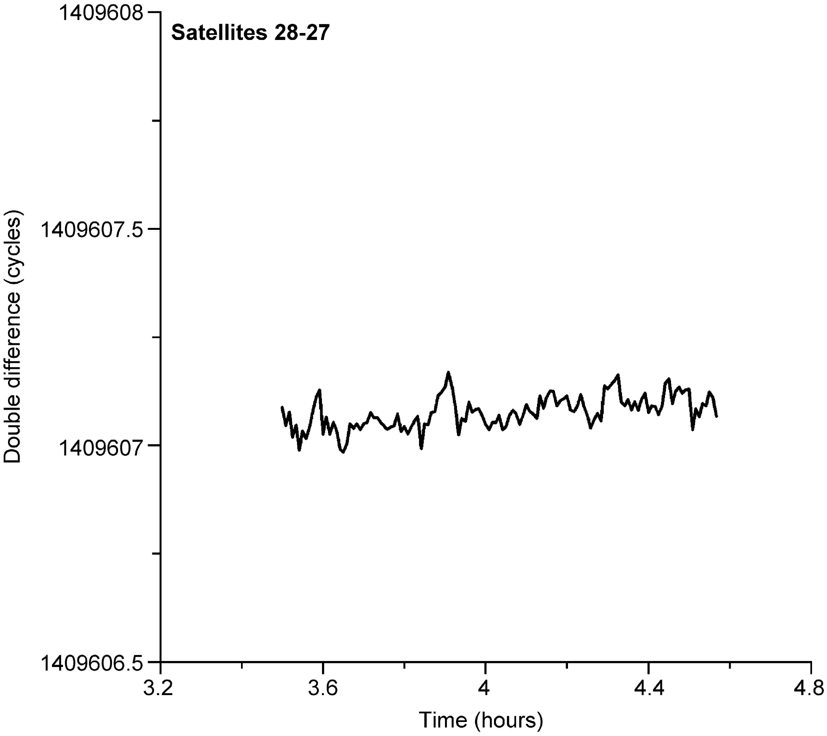

Fig. 5. Double difference of the L1 phase on DOY 359 in 2004, baseline Brussels–Saint-Gilles, satellite pair 28-27.

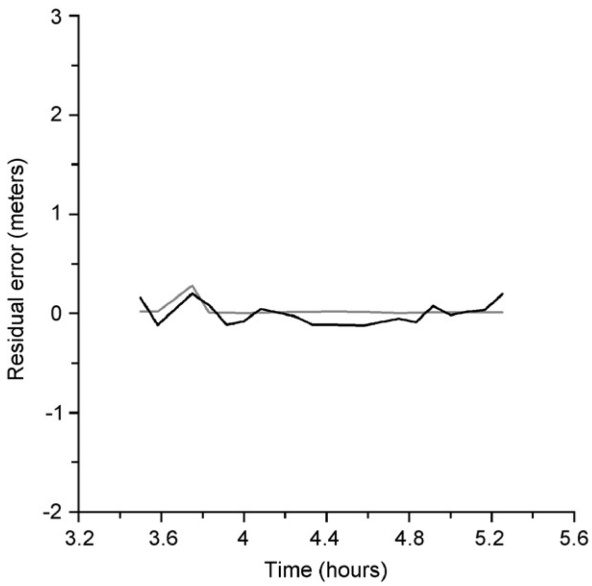

Fig. 6. Difference between station B true position (x component) and computed position without ambiguity resolution (black line) and with ambiguity resolution (grey line), baseline Brussels–Saint-Gilles, DOY 359 in 2004 (between about 3h00 and 5h30 UT).

component but similar results are obtained for the Y or Z components. Fig. 6 displays the difference between the computed and the true station B position (X component) before ambiguity resolution (black line) and after ambiguity resolution (grey line) from about 3h00 to 5h00. In most of the cases, after the ambiguity resolution process, the residual error is very close to zero except for a small peak before 4h00 which is not unusual with respect to RTK "nominal" accuracy: period where too few satellites are observed in common in the two stations (bad geometry) can also degrade the computed positions. Local effects like multipath can also degrade the computed position even on short baselines. Let us insist on the fact that the double difference 27–28 is only one of the double differences (given as illustration) which are used to compute station B position: as already explained, station B position is obtained from a least-squares process which is based on double differences formed using all the satellites in view in stations A and B.

Between 10h00 and 16h00, the ROB one-station software detected the presence of strong TIDs. A

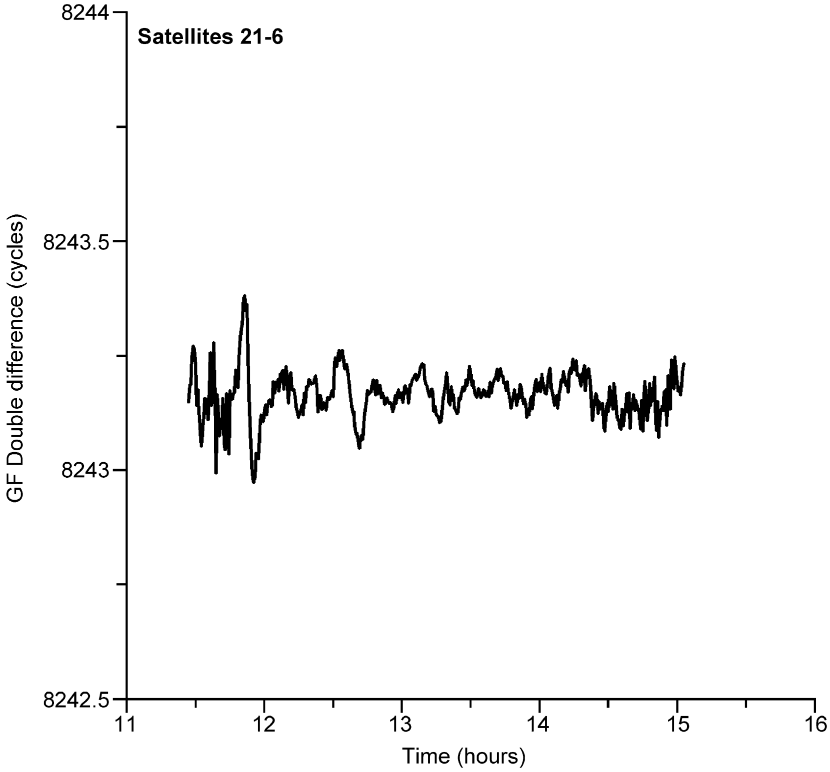

Fig. 7. Double difference of the geometric free combination on DOY 359 in 2004, baseline Brussels–Saint-Gilles, satellite pair 21-6.

variability of up to 0.63 TEC/min was detected. For example, Fig. 1 shows TEC variability observed along the track of satellite 21. Figs. 7 and 8 show, respectively, the double difference of the geometric free combination for satellite pair 21–6 and the corrected double difference of L1 phase measurement. The L1 double difference does not remain close to the integer but is affected by oscillations of which the amplitude reaches up to 0.5 cycles. These oscillations are clearly related to differential ionospheric effects. From the comparison of Figs. 7 and 8, it can be seen that the oscillations observed in the L1 double differences are anti-correlated with the oscillations observed on the geometric free double differences. The comparison between Eqs. (2) and (5) with Eq. (11) allows to understand the anti-correlation and the scale factor (1.8) existing between the ionosphere effects observed in the two figures. Indeed, if we compare the respective peak to peak values between about 11h45 and 12h15 on Fig. 7 (i.e. 0.41 cycle) and those on Fig. 8 (i.e. 0.74 cycle), we obtain a scale factor of 1.8 as expected from Eqs. (2), (5) and (11).

Ionospheric influences can be clearly seen in the results of our RTK simulation software. Fig. 9 shows the difference between the computed and the true station B position (X component) before (black line) and after (grey line) ambiguity resolution: on the one hand, the ambiguity resolution process degrades the quality of the computed position; on the other hand, the RTK position error after ambiguity resolution reaches more than 1.5 m due to the detected TIDs even on a such short baseline (with respect to the baselines of up to 20 km usually observed with RTK).

On November 20, 2003 (DOY 324 in 2003), a severe geomagnetic storm occurred. The ROB one-station software detected increased ionospheric variability (noise-like behaviour) from 10h00 to 24h00 UT with a peak between 15h00 and 18h00. TEC variability of up to 3 TECU/min was detected. This is one of the strongest TEC variability period even detected from 1993 to 2006 at Brussels using the ROB one-station software. Fig. 2 shows TEC variability observed along satellite 11 track on DOY 324 in 2003.

Fig. 10 shows the corrected double differences of L1 for satellite pair 11-18. Again, this double difference does not remain close to the integer value due to the detected noise-like variability which can

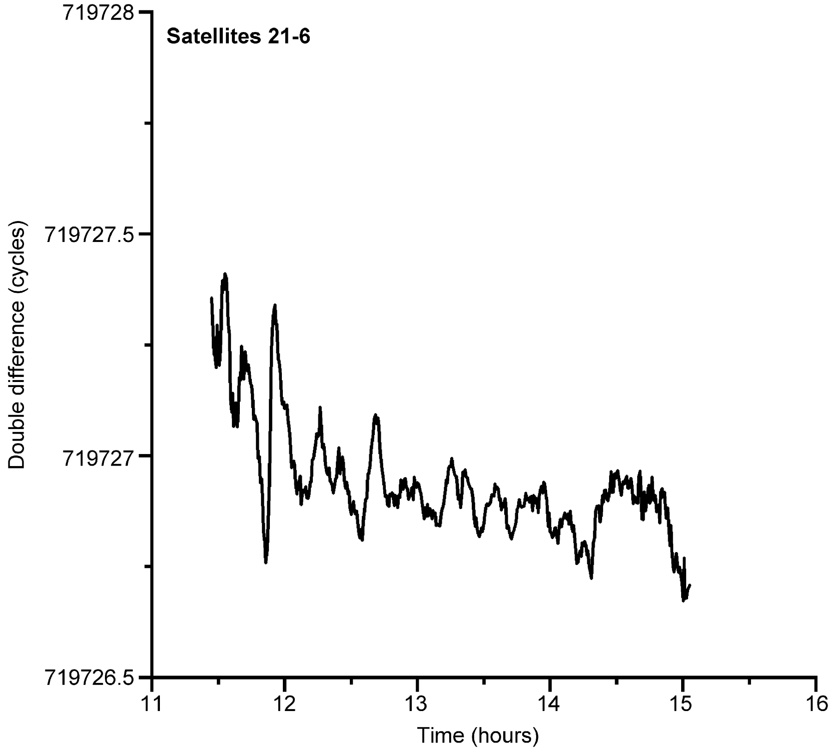

Fig. 8. Double difference of the L1 phase on DOY 359 in 2004, baseline Brussels–Saint-Gilles, satellite pair 21-6.

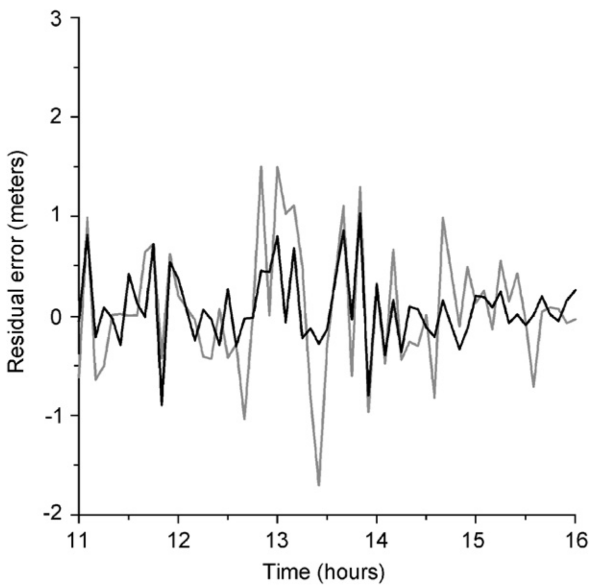

Fig. 9. Difference between station B true position (x component) and computed position without ambiguity resolution (black line) and with ambiguity resolution (grey line), baseline Brussels–Saint-Gilles, DOY 359 in 2004 (between 9h00 and 16h00 UT).

be seen in the double difference of the geometric free combination (Fig. 11): this proves the ionospheric origin of the variability observed in the L1 double difference. The effects of the geomagnetic storm on RTK positioning can be seen on Fig. 12 which displays the difference between the computed and the true station B position (X component) without ambiguity resolution (black curve) and with ambiguity resolution (grey curve). Again, it can be seen that the ambiguity resolution does not improve the quality of RTK positions. Errors of more than 1.5 m (in absolute value) are observed. By comparing Fig. 9 and 12, we can see that strong TIDs detected on DOY 359 in 2004, a day where the background ionospheric activity was low (mean daily TEC: 5 TECU, maximum TEC: 10 TECU) have the same influence than ionospheric variability due to a severe geomagnetic storm on RTK positioning even used on a short baseline (4 km).

6. Conclusions

In this paper, we do not propose a new technique for the mitigation of ionospheric effects but we present a software, which allows to obtain a quantitative assessment of the influence of ionospheric small-scale variability on the so-called RTK positioning technique. In a first step, the presence of small-scale structures (TIDs, ionospheric noise-like

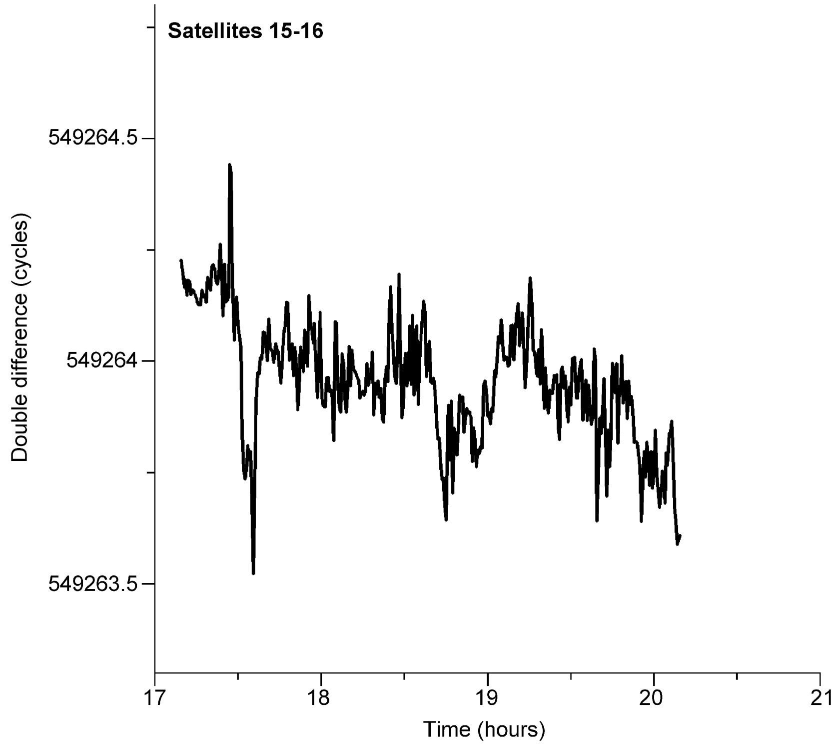

Fig. 10. Double difference of the L1 phase on DOY 324 in 2003, baseline Brussels–Saint-Gilles, satellite pair 15-16.

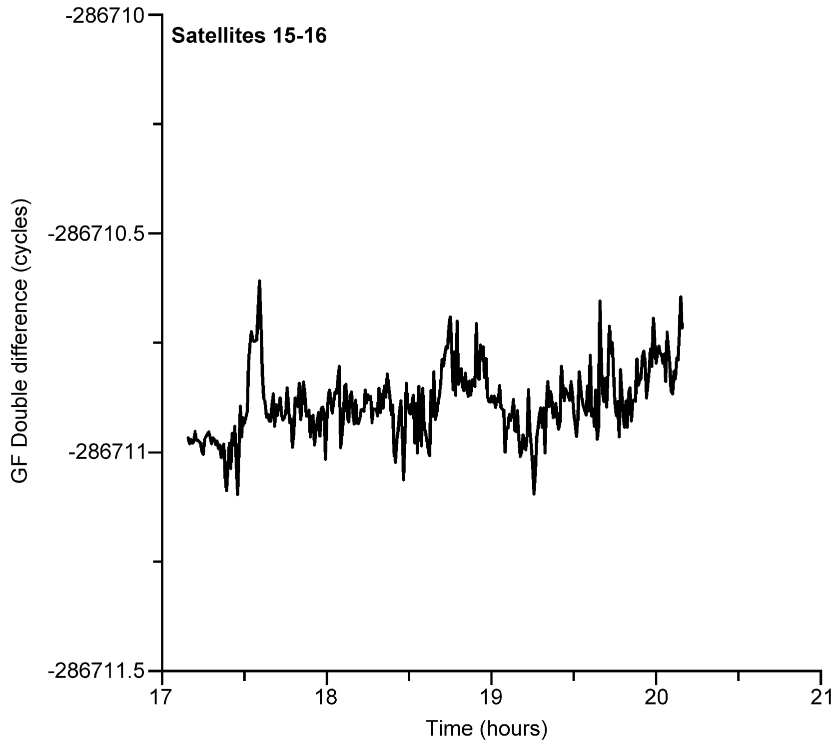

Fig. 11. Double difference of the geometric free combination on DOY 324 in 2003, baseline Brussels–Saint-Gilles, satellite pair 15-16.

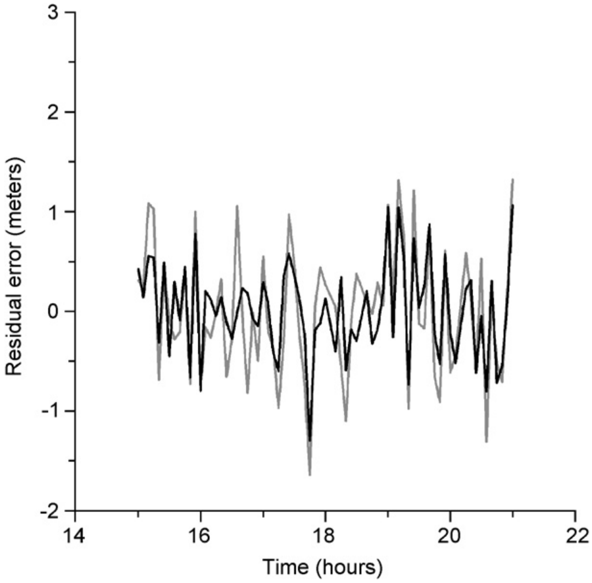

Fig. 12. Difference between station B true position (x component) and computed position without ambiguity resolution (black line) and with ambiguity resolution (grey line), baseline Brussels–Saint-Gilles, DOY 324 in 2003 (between about 15h00 and 21h00 UT).

behaviour) is detected using a dedicated technique, which monitors GPS–TEC high-frequency changes based only on data from one station. The influence of such a structure on RTK positioning depends on the distance between the reference station and the mobile user and on the size of the ionospheric structure. A first assessment of the differential ionospheric error can be obtained from the (ambiguous) double difference of the geometric free combination. In order to obtain a direct quantitative assessment of the RTK positioning error, we developed a software, which is similar to the software used by RTK users on the field. The software uses permanent station data of which the position is precisely known to simulate the RTK reference station (station A) and the mobile user (station B). When ionospheric disturbances cause differential ionospheric variability, it is then possible to compare the computed with the true station B position what provides a direct quantitative assessment of the error.

In this paper, we apply the software to a 4 km baseline at Brussels and we analyse ionospheric effects in two cases:

- December 24, 2004 where strong TIDs were detected (TEC variability up to 0.6 TECU/min).
- November 20, 2003 where strong ionospheric noise-like behaviour was observed due to a severe geomagnetic storm (TEC variability up to more than 3 TECU/min).

We show that, in these two cases, similar effects are observed on RTK positions, which are affected by errors up to more than 1.5 m. We demonstrate that strong TIDs can affect RTK in the same way as a severe geomagnetic storm even on a short distance.

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