Ionospheric effects on precise navigation at regional and continental scales over Europe

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Abstract

As it is already known, the ionosphere is one of the most important source of errors that limits the capability of navigating with an GNSS receiver with errors of few centimeters, by means of solving the carrier phase integer ambiguities.
There are techniques that neglect the error in the phase integer ambiguity resolution due to the ionosphere, as the RTK technique. But its range is bounded to baselines up to 10 - 20 Km, depending on the ionospheric activity. Therefore, in order to extend the RTK technique, the ionosphere has to be modeled very accurately in real-time in order to minimize its contribution to the positioning error, by allowing the right fixing of the integer ambiguities.
In this work real-time ionospheric and geodetic models will be used to obtain the "super-truth" ionospheric differential delays between the reference stations at several distances. In this way, we will be able to determine the importance of the ionospheric error, and the performance of the navigation technique developed previously (Wide Area RTK), treating some additional fixed stations as rover.
The study covers a long period, the whole year 2002, and a wide range of distances, from regional baselines in the ICC network (distances of 20 km and greater), that it is the limit of the classical RTK, to continental baselines in the European IGS network (up to 2500 km).
The behavior of the ionosphere is studied, to characterize the sources of error (such as the existence of Travel Ionospheric Disturbances) that can seriously affect when the ionospheric corrections are interpolated to the users. In this way we will demonstrate during a period of one year that the subdecimetric navigation is feasible over long baselines, with a high degree of ambiguities resolved in real time.

1. Introduction.

The ionosphere, that is the part of the atmosphere above 60 km until 2000 km of the earth surface, is the main source of error in GPS applications. Its effects cause delays and advances to GPS code and phases, and due to the fact that the ionosphere is a dispersive media, their effect to the signal is dependent with the frequency. Then, the solar activity is one of the most important sources in the ionospheric behaviour. In such a way that in the neighbourhood of the solar maximum peak, 2000 - 2002, the ionization is maximum and can appear more frequently local effects such as the Travel Ionospheric Disturbances (TIDs), which are waves in the electron density of the ionosphere, among others. On the other hand, GPS works at two frequencies, f_1 = 1.2 GHz and f_2 = 1.6 GHz, which allows to cancel out the ionospheric effect in a 99 %, if a dual frequency receiver is used. However, it is possible, instead of cancel the ionospheric effect, to compute the Total Electron Content (TEC) of the ionosphere in order to study its behaviour. In this framework the international GPS service (IGS) established a set of international groups, the IGS Associate Analysis Centers (IAACs)[1], in order to compute Global Ionospheric Maps (GIMs) from GPS data in a daily basis [1]. This working group started to send their GIMs at 1st June 1998, and the common IGS GIM was approved to be broadcasted at May 2003. With these GIMs the ionospheric effect can be reduced to 10% - 20%, see [5], that it is better than the 50 % that corrects the Klobuchar model.
In real time positioning techniques the accuracy, cancelling the ionosphere and floating the phase ambiguities, is about submeter level. To overcome this lack of accuracy and to achieve better precisions, techniques based in the differential GPS (DGPS) can be used, since with these ones, a set of parameters are transmitted to the user in order to correct as much as possible sources of error in the user location [2]. These techniques have accuracy from meter to centimeter level depending on the baseline, and the kind of transmitted corrections. The most precise technique is the so-called Real Time Kinematics (RTK), which can be applied to baselines about 20 km depending on the ionospheric activity, since this technique basically neglects the effect of the ionosphere. Therefore, in order to extend these techniques the modelling of the ionosphere has to be taken into account to maintain the subdecimeter accuracy. A way to do that is using the Wide Area Real Time Kinematics (WARTK) technique, see [4] for details, which use two programs in parallel, a geodetic and a ionospheric ones, in order to fix the phase ambiguities to their integers values in the fixed stations, specially to provide an accurate ionospheric correction to roving users.

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The purpose of this work is, first, to use the WARTK technique as a tool the measure the performance of the different IGS GIMs, with the help of the true computed ionospheric corrections for several long baselines over Europe. And, second, a local study, in a regional network, in order to quantify the ionospheric circumstances that can limit the RTK techniques. The presence of the TIDs will be studied since they cause a non-linear behaviour of the ionosphere that is translated in worst interpolated ionospheric corrections to the roving receivers.

2. Obtaining very accurate ionospheric delays.

In DGPS techniques, it is usual to solve the navigation equations by means of using the double differences. This kind of combinations allow the reduction of the common source of errors for the stations and satellites involved in the computation. In the case of the Real Time Kinematics (RTK) the assumption that the ionospheric effect cancels out is no longer valid for baselines greater than 10 – 20 km. This is the main limiting factor in RTK and it has to be overcome by means of computing the differential ionospheric correction between pairs of satellites and receivers, from now on ∇ΔSTEC. In order to do it, the use of the Wide Area RTK (WARTK) technique [4] is necessary to allow the computation of very precise ∇ΔSTEC with an accuracy of few millimetres for long baselines.

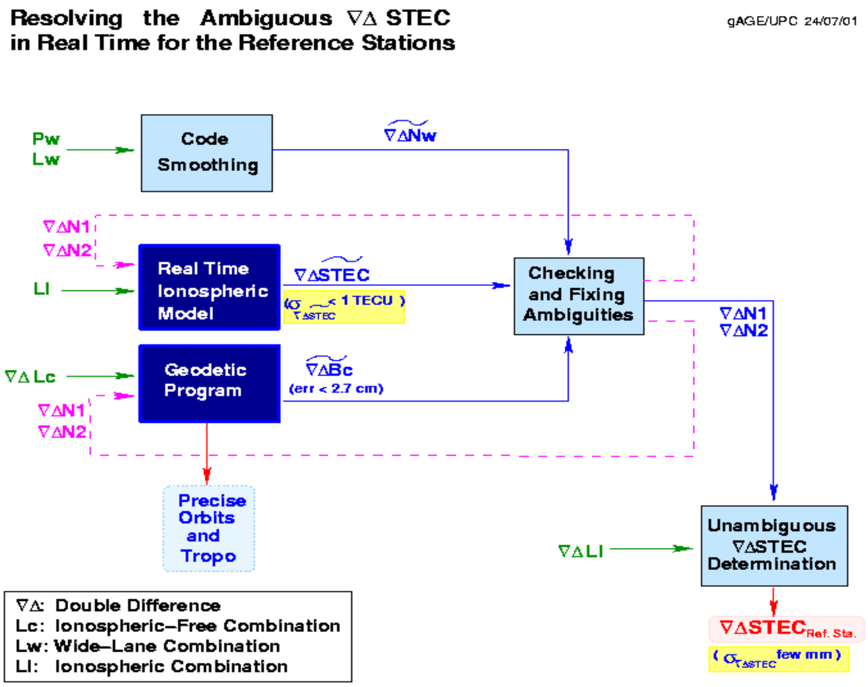

Figure 1: Algorithm scheme for the WARTK technique.

The technique works as follows. In a given GPS station network, there are some stations that have known coordinates, they will be the reference or fixed stations, and inside the network there are some users or roving receivers. Thus, in the fixed stations, a geodetic and an ionospheric program run in parallel in order to compute the precise ∇ΔSTEC at those stations (see figure 1). In the geodetic program the $\nabla\Delta B_C$ (Double difference of the L_C -free ionospheric combination- ambiguity) is computed with an accuracy of some centimetres, notice that this ambiguity is floated and it is not an integer number. The ionospheric program computes, using a tomographic description of the ionosphere [3], an enough precise ∇ΔSTEC, with an accuracy better than 10.5 cm of L_I, which allows to fix the $\nabla\Delta N_W$ (double difference of the L_W -wide lane combination- ambiguity), rounding up to the nearest integer. Then, both L1 and L2 ambiguities can be fixed, allowing recomputing the ∇ΔSTEC with a millimeter level error. Afterwards, these ∇ΔSTEC can be interpolated to the roving receiver location (see figure 2).

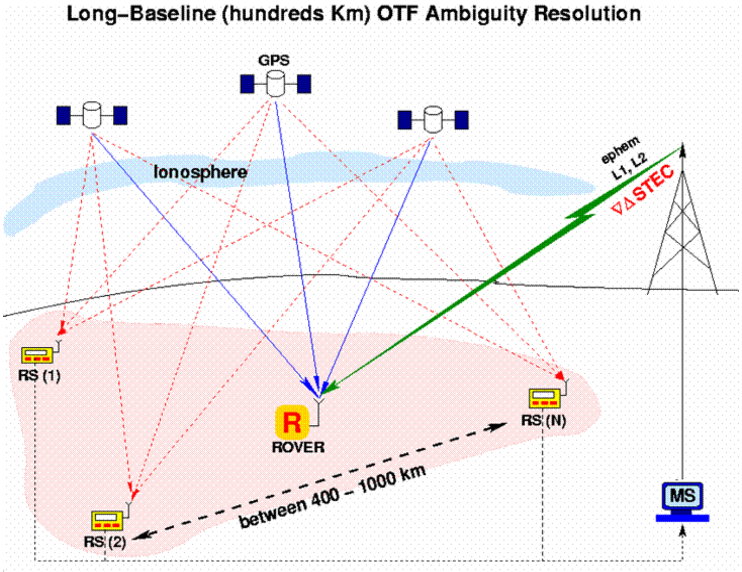

Figure 2: Conceptual picture of the WARTK technique while sending the ionospheric corrections.

These very accurate values of ∇ΔSTEC between pairs of fixed station can be used to test any ionospheric model, such as the IGS GIMs. Thus, in this work, all the stations involved in the experiment have been treated as fixed stations. With this configuration it has been possible to have very accurate ionospheric corrections, ∇ΔSTEC, among all the stations. This fact allows considering some stations as roving receivers, and then, studying the interpolated ∇ΔSTEC performance in function on the behaviour of the ionosphere, as it will be explained in next sections, for different baselines.

3. Scenarios and results

In this work, two GPS networks at different scales have been used in order to quantify the different scales of the study of the ionosphere. Firstly, a continental GPS network has been used to show the performance of the IGS GIM's ∇ΔSTEC regarding to the very accurate computed values with the WARTK technique. Secondly, a regional GPS network has been used in order to study the limiting factors to extend the classical RTK technique to longer baselines. In fact, the study is centered on the ionospheric variability which could difficult the subdecimeter navigation.

3.1. Performance of the IGS global maps at continental scale.

In a continental GPS network, using IGS GPS receivers, with baselines up to 2500 km over Europe (see figure 3), the IGS IONEX ionospheric estimates have been compared with the accurate ionospheric corrections computed with WARTK in order to determine their performance. The reference station for the ∇ΔSTEC is EBRE. In this data set, there are data from the IAACs for 18 days, from 22nd April 2003 to 10th May 2003, using their Global Ionospheric Maps (GIMs). The IGS GIMs, which comes from combining the different IAACs estimations, will be considered as well. With these GIMs, the predicted double differences are compared with the very accurate ∇ΔSTEC data.

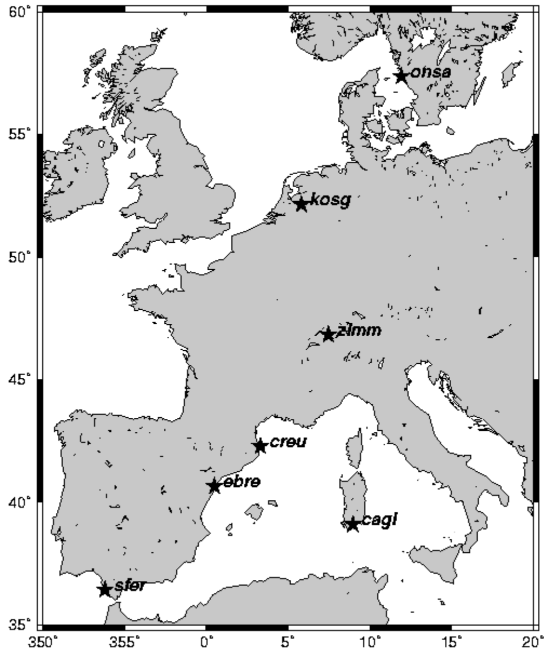

Figure 3: Map of the continental network used in the IONEX comparison. Note that MNTC is the reference station for the double differences.

The study has been conducted not only using the different distances to the reference station (EBRE) of the double differences, but considering different latitudes as well. The baselines range from 280 km to 2020 km with latitude differences from -4° to 16°. With this configuration it is possible to do statitistics as a function of the distance and latitude differences in order to determine the performance of the different available GIMs (see table 1).

	CREU (288 km; 1.50°)	CAGL (748 km; -1.68°)	SFER (757 km; -4.35°)	ZIMM (875 km; 6.05°)	KOSG (1326 km; 11.36°)	ONSA (2018 km; 16.60 °)
	RMS (m)	RMS (m)	RMS (m)	RMS (m)	RMS (m)	RMS (m)
CODE	0.09	0.13	0.12	0.14	0.18	0.20
ESA	0.19	0.18	0.24	0.22	0.29	0.44
JPL	0.10	0.14	0.12	0.14	0.18	0.22
UPC	0.12	0.15	0.15	0.15	0.17	0.22
IGS	0.08	0.11	0.11	0.11	0.14	0.18

Table 1: Results showing the RMS performance of the different IGS GIM's as a function of the distance and latitude difference to the reference station EBRE.

As it can be seen in table 1, the best performance corresponds to the IGS GIM. This GIM has always slightly better performance or at least equal than the best IAAC GIM. The other GIMs have more or less the same performance. These results are compatibles with other comparisons performed with TEC data [5] come from TOPEX/Poseidon satellite altimeter.

The figure 4 shows both dependencies of the $\nabla\Delta$STEC RMS over baseline length and latitude differences. This last dependency is due to the fact that the ionosphere has a strong correlation with the latitude, with higher values at low latitudes over Europe.

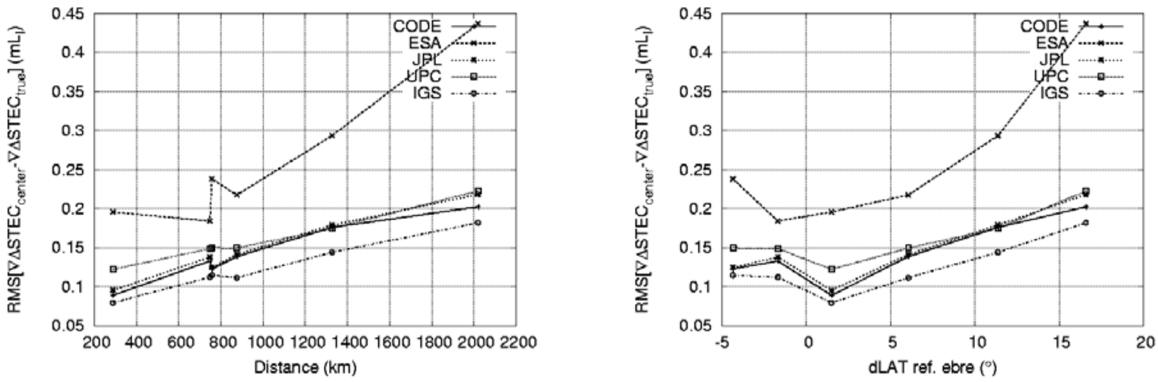

Figure 4: In the right hand side it is depicted the RMS of the ∇ΔSTEC as a function of the distance to the reference station EBRE. In the left hand side the same RMS is depicted as a function of the latitude difference to the reference station EBRE.

3.2. Ionospheric variability affecting the subdecimeter navigation.

As it has been mentioned before, there is another GPS network involved in this work (see figure 5). This network has a regional scale with baselines up to 290 km, that are quite shorter than the baselines used in the previous section. This network is centered at the north-east of the Iberian Peninsula, using the CATNET network of the Cartographical Institute of Catalonia (ICC) and two gAGE/UPC receivers. The stations are: Avellaneres (AVEL), Montcada (MNTC), Llívia (LLIV), Creus (CREU), Bellmunt (BELL), Planes (PLAN) and Ebre (EBRE) that belongs to ICC; and the gAGE/UPC stations located at Barcelona (UPC1) and Castelldefels (UPC2). With these stations the study of the performance of the WARTK and RTK in terms of ionospheric variability has been conducted, finding a relationship between the presences of TID with the poor performance in the ∇ΔSTEC interpolated to the users.

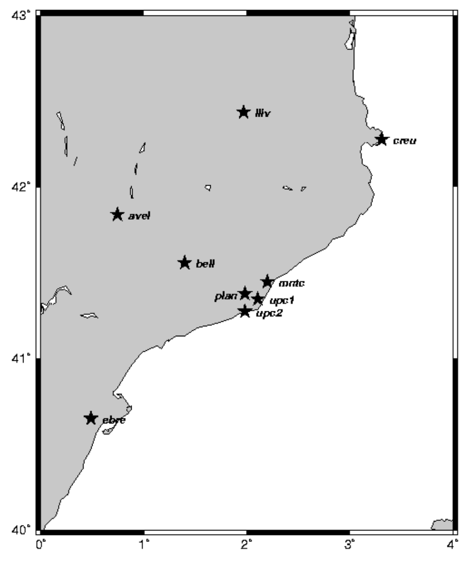

Figure 5: Map of the regionl network used in this work. Note that MNTC is the reference station for the double differences.

The period of the study covers the whole year 2002 taking observations once a week, more concretely every Thursday of the year. In order to compute the very accurate ∇ΔSTEC data, all the stations have been considered as fixed stations, being MNTC as the reference of the double differences. Then, once the "truth" data have been computed, several stations have been treated as a roving receiver in order to quantify the performance of the real-time interpolated ∇ΔSTEC as a function of the distance to the reference station (see table 2). The distances among the rovers and the reference station considered range from 10 to 70 km which allow the evaluation of the RTK features (see table 3 for details). In this context, the cases in which the ∇ΔSTEC is below 2.7 cm have been accounted as well in order to determine if it is possible to neglect them, as the RTK does.

STATION	DISTANCE TO MNTC (km)
UPC1	13
PLAN	20
UPC2	30
BELL	68

Table 2: Distances of the roving receivers to the reference station.

In this framework, a simple linear model has been used in order to correct the contribution of the ionosphere at the roving receiver. Then, the number of occurrences below 2.7 cm has been considered again in order to show how a simple model can extend the classical RTK (see table 3 for results).

	UPC1 (7120)	PLAN (10917)	UPC2 (6584)	BELL (16718)
No iono.	98 %	92 %	85 %	58 %
With $1/d^2$	98 %	94 %	85 %	87 %

Table 3: Percentage of successful ambiguity fixing considering the different roving receivers without correcting the ionosphere and using a simple linear model to interpolate the values. Notice that all the occurrences have been taken into account when the ∇ΔSTEC has been fixed between all the reference stations.

As it can be seen in table 3 the number of ∇ΔSTEC that can be neglected from the point of view of the ambiguity fixing(first row) decrease very fast as a function of the distance, in UPC2 (30 km) there are 85% of the ∇ΔSTEC below the corresponding threshold of 2.7 cm, while there are about 58 % at BELL (68 km). With these results, it is expected that a user could navigate with errors of few centimeters to distances of 20 – 30 km (success of 85% to 92% in this study).
Then, for longer baselines the subdecimeter navigation is not possible. Therefore, to extend the range of the classical RTK it is necessary to transmit accurate enough differential ionospheric correction to the roving receiver, using the WARTK as it has been mentioned before. And using a simple interpolation model, in this case, with weights proportional to $1/d^2$, it is possible to increase the ambiguity fixing success to about 87% at the station BELL (68 km).
In order to take into account the factors limiting the extension of the classical RTK, it is important to study the ionospheric variability. In this sense, the study of the influence of the TID in the ∇ΔSTEC becomes a critical issue when it is desired navigate with subdecimeter accuracy, since the TID cause non-linear behaviour in the ∇ΔSTEC which significantly decreases the interpolation performances.

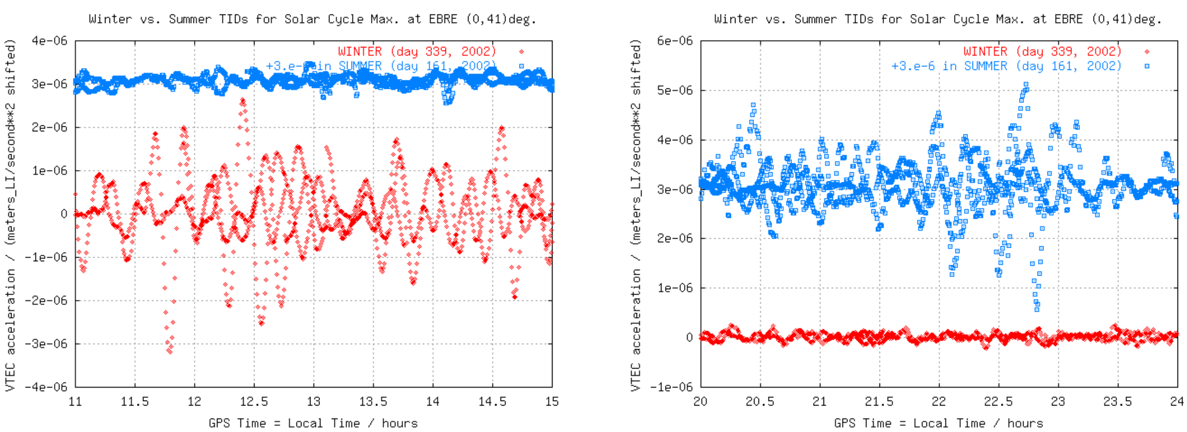

Figure 6: *STEC drift rate* for two typical days, one chosen on winter and the other on summer as a function of the local time. In the left hand side it is depicted the variation during the winter midday. And in the right hand side there is depicted the variation during the summer midnight.

The vertical *TEC drift rate* (second derivative of time) provided a good index of the ionospheric variability. In order to take into account the presence of the TIDs on a network, the *TEC drift rate* of the vertical TEC is useful to detect them because it presents strong variations as it can be seen in figure 6.
It is evident in this example that there are TIDs in the winter day around the noon and in the summer days around the midnight. It can be seen in figure 7, bottom plot, that this result is persistent during all the year 2002 using the data of EBRE. In this plot, it has been represented the *TEC drift rate* RMS as a function on the day of the year (horizontal axis) and local time (vertical axis). It can be seen that the higher *TEC drift rate* RMS is concentrated around the noon in the winter, and around midnight in summer.
On the other hand, in the same figure 7, the ambiguity success, in fractional values, for the longest baseline studied in the regional network (BELL treated as roving receiver, referred to MNTC, about 68 km length) is represented as well in terms on the day of year (horizontal axis) and local time (vertical axis). It is evident, comparing with the bottom plot, the high correlation between both ∇ΔSTEC performance and TEC variability.

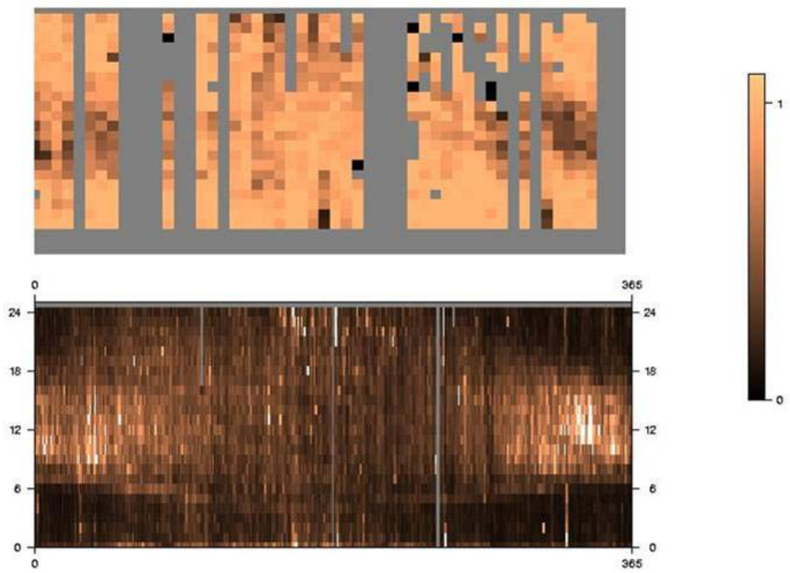

Figure 7: Up: ratio of the number of the Δ∇STEC values below 2.7 cm. at the station BELL Down: *TEC drift rate* showing the presence of TIDs: In both pictures the x-axis represents days, and the y-axis the time in hours.

Then, the next step has been to extend this study to the maximum period of time as possible for this region. To do it, the parameter *TEC drift rate* RMS has been computed for the station EBRE since its availability, as first permanent GPS station established in this region during the end of the year 1996 until now (see figure 8).

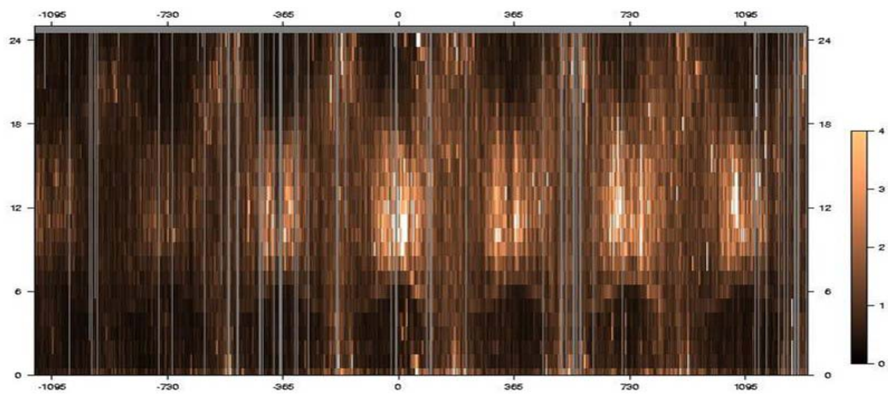

Figure 8: Ratio of the number of the Δ∇STEC values below 2.7 cm. at the station EBRE since the year 1996. The x-axis represents days, the 0 days corresponds to the 1st January 2000, and the y-axis the time in hours.

As it could be expected the number of TIDs is high about the Solar Maximum peak. And it can be seen that there are more activity about the noon winter (that it is compatible with the results found in [7]), and in the summer midnight (compatible with [6]). It is during these periods in which the performance of the ionospheric interpolation is more critical. And it has been matter of investigation the use of more efficient interpolation procedures used than the simple interpolation procedure, for illustration purposes, used in this study.

4. Conclusions

In this work, two kinds of studies have been performed regarding to the ionospheric corrections. First, a study with the IGS GIMs was conducted, showing that there are good agreement among the most part of centers at centimeter level. In this study is also compute the performance of the IGS common GIMs, proving that have at least the same or better performance that the best IAAC GIM when the $\nabla\Delta$STEC are studied. In this context, it has been shown that the loss of accuracy is dependent on both the difference of latitudes and the distance. The second study performed in this work was related with the ionospheric behaviour on a regional GPS network and its impact on real time positioning. This study has quantified the effect of the ionosphere in the $\nabla\Delta$STEC, with roving baselines from 10 km to 70 km, showing that with a simple model and the help of the WARTK technique it is possible to extend the classical RTK technique more than 3 times its baselines. Another interesting result is the existence of a correlation between the loss of performance on the $\nabla\Delta$STEC interpolation and the increasing of the TID occurrences, which are maximum in the winter midday and summer midnight, being strongly dependent on the Solar cycle.

5. Acknowledgments

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