MSTID Detection, Characterization and Modelling: A Key Point to Improve the Precise GNSS Navigation

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ABSTRACT:
The main focus of this paper is to show how the better knowledge of the behaviour of the more common ionospheric perturbations (the so called Medium Scale Travelling Ionospheric Disturbances, MSTIDs) can significantly improve the precise GNSS real-time positioning. In order to do this, three main studies has been carried out: 1) To develop a simple but accurate MSTID detection and characterization algorithm. 2) To apply this technique to extract the MSTID worldwide behaviour, in terms of occurrence, velocity, azimuth and period. 3) To form a simple blind MSTID model, summarizing these results (the main point detailed in this manuscript). This model is applied to real-time positioning scenarios, to show the significant reduction of positioning error. This increase of performance is achieved in both "classical" short baselines of few tens of kilometres (those covered by RTK and VRS techniques), as well as in very long baselines of hundreds of kilometres (by using the Wide Area RTK technique –WARTK– developed by the authors in previous works), providing in this way a carrier phase based GNSS navigation service with typical errors of few centimetres.
Key words: Ionospheric perturbations, Precise GNSS navigation, MSTID, Carrier phase based GNSS navigation, Ionospheric tomography.

RESUMEN:
El objetivo de este artículo es mostrar como un mejor conocimiento de las perturbaciones ionosféricas más usuales (las llamadas perturbaciones ionosféricas viajeras de escala intermedia -del inglés, MSTID-) puede mejorar significativamente el cálculo preciso en tiempo real de la posición con sistemas de navegación por satélite (del inglés, GNSS). En este sentido, tres estudios se abordan en este trabajo: 1) El desarrollo de un algoritmo simple pero preciso de detección de las MSTIDs. 2) La aplicación de esta técnica para estudiar el comportamiento global de las MSTIDs. Y sobre todo, 3) la construcción de un modelo predictivo simple, que recoja los resultados principales previos. Este modelo se aplica a escenarios de posicionamiento preciso en tiempo real, con una reducción significativa del error. Esta mejora en el posicionamiento se consigue tanto en líneas de base "clásicas", es decir de hasta pocas decenas de kilómetros (cubiertas por técnicas comercializadas como RTK y VRS), como para líneas de base muy largas, de varios centenares de kilómetros, usando por ejemplo la técnica de "Wide Area RTK" (WARTK), desarrollada por los autores en trabajos previos, proporcionando un servicio de navegación basado en la fase de las portadoras GNSS, con errores típicos de unos pocos centímetros.
Palabras clave: Perturbaciones ionosféricas, navegación precisa GNSS, MSTID, navegación basada en la fase de la portadora, tomografía ionosférica.

1. INTRODUCTION

The feasibility of real time GNSS navigation, at distances greater than few tens of kilometers from a reference site, is strongly related to the capability of providing accurate differential ionospheric refraction values to the user, in real-time. If such provided differential STEC values are very accurate (more than 0.25 TECU, about 4.5 cm in L1 GPS frequency, see Hernández-Pajares *et al*. 2000), then it is possible to provide a GNSS positioning service with errors below ten centimeters at continental scale, thanks to the so called Wide Area Real Time Kinematic technique, being in constant development by the authors since 1999. It will allow extending the RTK from Local Area to Wide Area. With this capability just a few dozens of fixed reference GNSS receivers, such as the EGNOS RIMS, would be enough to ensure a sub-decimeter positioning service in Europe for example. Such accuracy can be achieved instantaneously with Galileo and other 3-frequency systems, and in about 1 minute with GPS (see Figure 1 and Figure 2 and Hernández-Pajares *et al*. 2003a-b, 2004 for details).

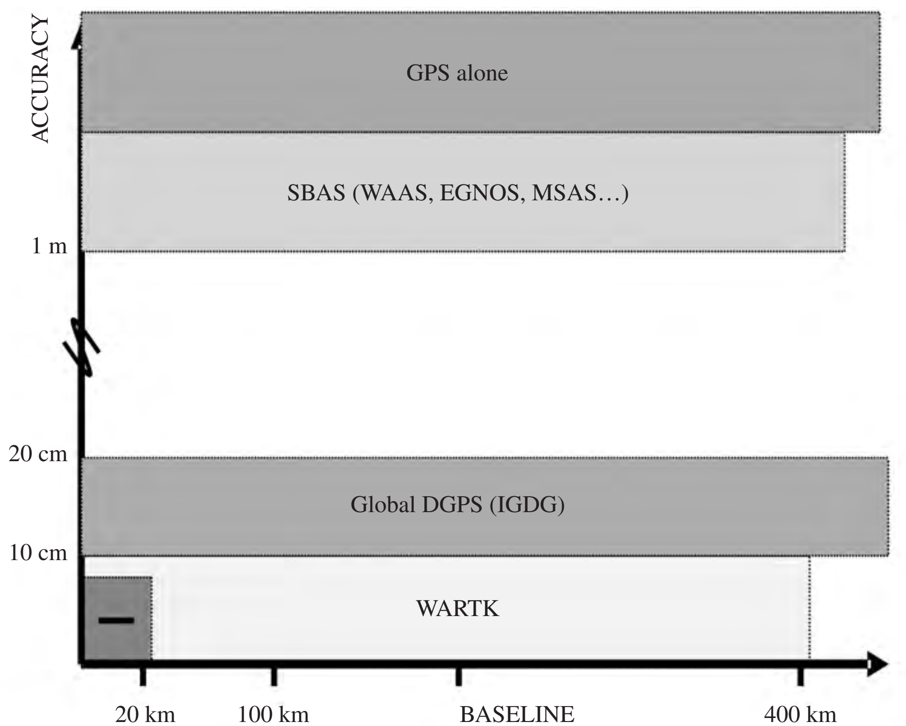

Figure 1.- Plot showing the accuracy versus baseline length (from the nearest reference site) for different GPS systems. The WARTK system (WARTK-2 and WARTK-3) fills a gap, with sub-decimeter errors at hundreds of kilometers' baselines. In the case of WARTK-3 such centimeter-level accuracy can be achieved instantaneously most part of the time (see next figure).

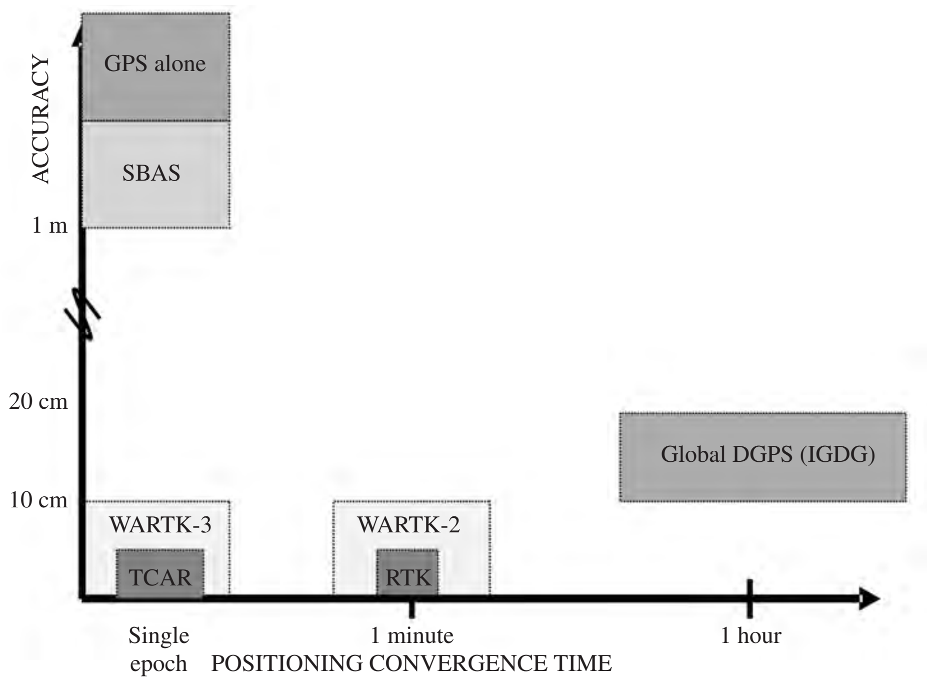

Figure 2.- Plot showing the accuracy versus positioning convergence time for different GPS systems. The WARTK system (WARTK-2 and WARTK-3) fills a gap, with sub-decimeter navigation errors at hundreds of kilometers baselines lengths. In the case of WARTK-3 such centimeter-level accuracy can be achieved instantaneously most part of the time.

Two of the main typical error sources to deal in this accurate ionospheric modelling are: (1) the differences between the user and reference site ionospheric states and paths. This large-scale effect is especially important for long baselines, at low latitudes, or during Solar Maximum or geomagnetic activity conditions. It has been studied and modelled by the authors in previous works (see for example Hernández-Pajares *et al*., 2000, 2002). And another effect, (2), at shorter scales: the ionospheric perturbations, being the more frequent the so called Medium Scale Traveling Ionospheric Disturbances (MSTIDs).

As will be presented in next section, the MSTIDs are wave-like signatures appearing in the STEC with typical amplitudes of several TECUs and wavelengths of 100-300 km. The MSTIDs show a strong seasonal behavior, which seems related to Solar Terminator and associated Atmospheric Gravity Waves, in such a way that they mostly happen in the day-time in winter season, moving towards the equator with typical horizontal velocity of ~100-250 m/s, and mostly happen in the night-time in summer season moving westward with velocities of ~50-150 m/s (see Hernández-Pajares, Juan and Sanz, (2006), hereinafter HJS06). Such strong seasonal behaviour makes feasible a simple MSTID modelling for practical applications such as precise GNSS navigation, which is the main goal of this work.

2. MEDIUM SCALE TRAVELLING IONOSPHERIC DISTURBANCES

Travelling ionospheric disturbances (TIDs) are plasma density fluctuations that propagate through the ionosphere at an open range of velocities and frequencies. TIDs have been observed in most of the ionospheric measurements (Faraday rotation, ISR, VLBI, GPS). Many authors distinguish between Large scale TIDs (LSTIDs) and Medium Scale TIDs (MSTIDs). LSTIDs present a period greater than 1 hour and moving faster than 300 m/s. They seem to be related to geomagnetic activity and Joule effect at high latitudes, which produce thermospheric waves towards lower latitudes. MSTIDs have shorter periods (from 10 min to 1 hour) and move slower (50-300 m/s). The origin of MSTIDs seems to be more related with meteorological phenomena like neutral winds or solar terminator which produce atmospheric gravity waves manifesting as TIDs at ionospheric heights.

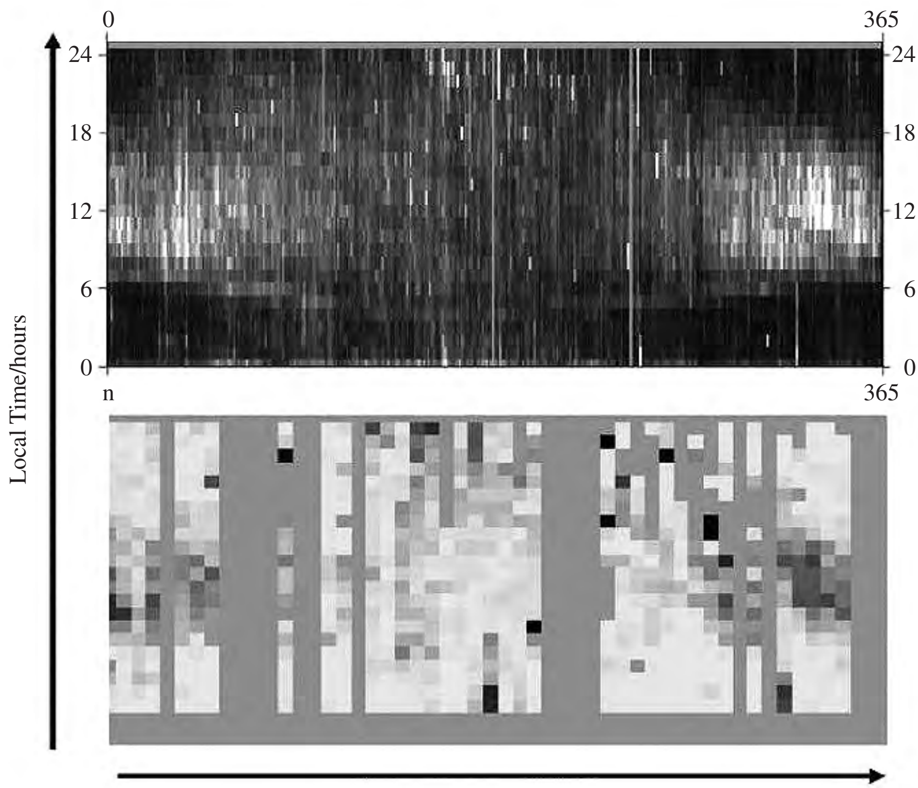

Figure 3.- This figure shows the relationship between the distribution of the detected TID (top-side plot in terms of day of year 2002 and local time, rescaled at arbitrary units –more brilliant colour represents higher MSTID activity-), and the error in the ionospheric correction for a roving receiver at 70km far from the nearest receiver (in terms of day of year 2002 and local time, and rescaled as well –being greater errors indicated by darker colour-), in the ICC GPS network in Catalonia, at the NE of Spain.

Despite the small amplitude of the MSTIDs, typically of tenths of a TECU in STEC GPS observations, several authors (Chen *et al*., 2003; Wanninger, 2004; Hernández-Pajares *et al*., 2001) have shown that the presence of such ionospheric disturbances can cause a significant performance decrease on precise GPS navigation. This is because, for precise navigation, it is required that the differential ionospheric delays should be predicted with a very high precision, better than 0.25 TECU (such as in the case of the above mentioned WARTK technique).

An example of high correlation between poor simple ionospheric interpolation performance and the occurrence of MSTIDs can be identified in Figure **3**, suggesting as well a Seasonal MSTID occurrence pattern. As it can be seen in this figure, the poorest results in ionospheric prediction occur at the same time as the MSTID detection. This is the reason why we decided to focus on the improvement of MSTIDs detection and characterization in HJS06, in order to confirm the seasonal occurrence as far as the seasonal dependence of propagation parameters such as velocity, azimuth and periods. This has been a previous step (summarized in next section) to the real-time modeling, the main target of this paper.

3. TIDS OCCURRENCE FOR MORE THAN HALF SOLAR CYCLE

As mentioned above, simple methods of detecting and characterizing the MSTIDs (see example in Figure 4), with data coming from 4 different

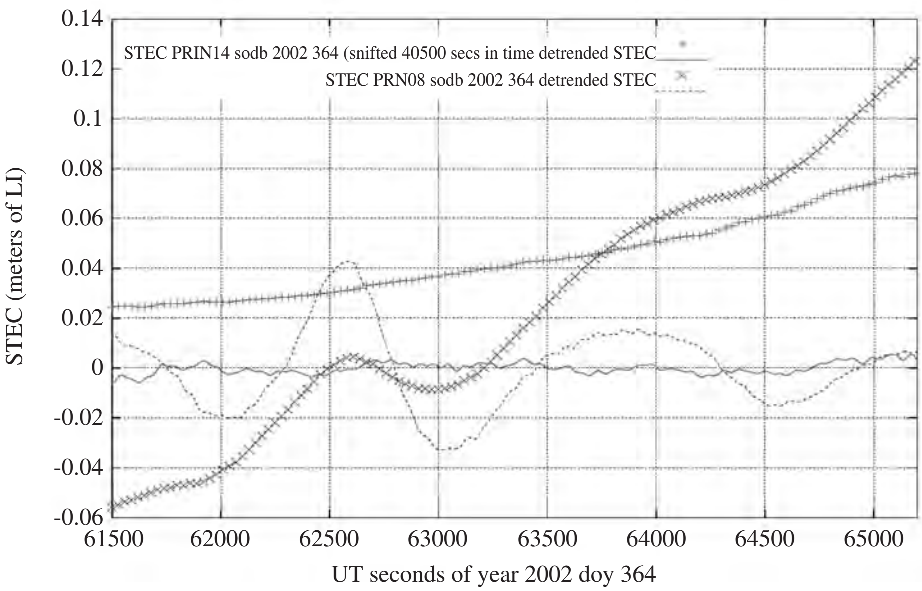

Figure 4.- Two examples of the detrending method acting over one STEC series without apparent TIDs (“x” and “-“ signs, PRN14) and other where a TID is present (“+” sign and line, PRN08). In both cases the STEC has been divided by an obliquity factor in order to diminish the variation in the time window.

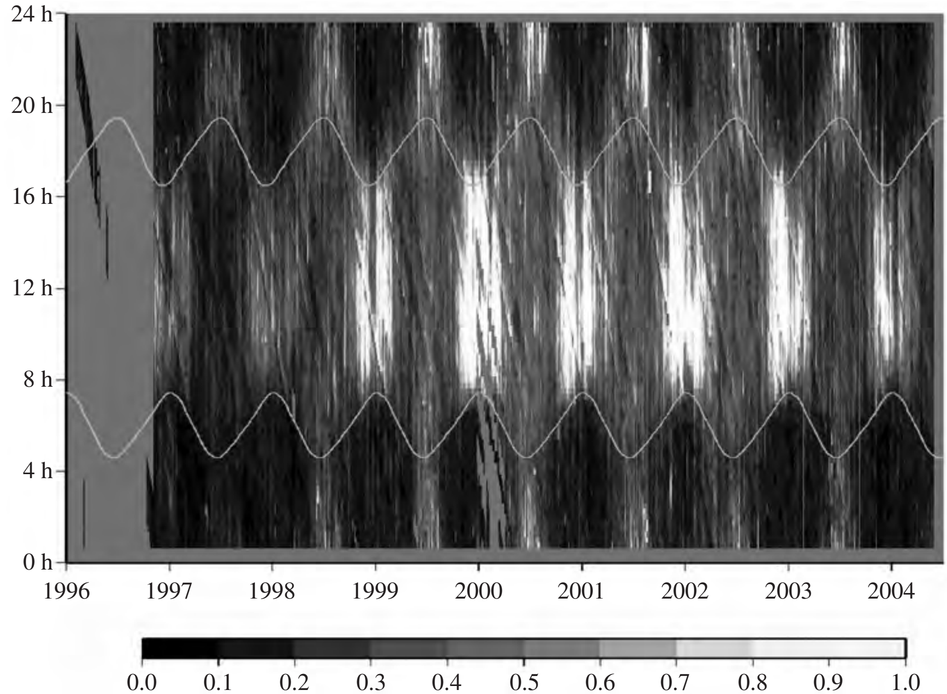

Figure 5.- Rescaled amplitude of MSTIDs detected over the EBRE GPS receiver (40.6N, 0.5E). Horizontal axis represents the day in years, and the vertical axis represents the local time in hours. The continuous line represents the Solar Terminator.

worldwide distributed ground local networks of GNSS receivers, have been developed by the authors, in HJS06. Let us summarize its main results in order to build a simple real-time MSTID model, useful for precise GNSS navigation applications.

The TIDs occurrence since end of 1996 at EBRE GPS permanent receiver (NE Spain, 0ºE 40ºN, Figure 5) repeats the seasonal dependence (midday winter, midnight summer), apparently confined by the terminator, and modulated by the Solar Cycle. Similar results are obtained for south hemisphere in terms of the local season and local time (HART, South-Africa, 28ºE 26ºS). On the other hand it can be seen that the corresponding TIDs affecting WARTK are Medium Scale TIDs with Power Spectral Density quite concentrated (wave packets) at around 1mHz (periods of about 15-20 minutes).

4. SUMMARY OF THE MSTID PARAMETERS

In HJS06 optimal procedures to estimate MSTID parameters and the corresponding results from four local networks worldwide distributed (in Venice, California, Middle East and New Zealand) were depicted during 2002-2003, with low geomagnetic activity (Kp<4), and fulfilling the MSTIDs the simple assumption of planar wave propagation. We refer the reader again to this reference for additional details on the procedure, results and discussion. In this paper, we are going to summarize such results, taking into account, as mentioned above, that our main goal goes beyond the above mentioned paper scope: towards the generation of a simple real-time MSTID model and its application to GNSS navigation. And hence the overall results (corresponding to results obtained in 2002-2003 from the above mentioned local networks) are summarized in Table 1, in terms of the main Local Time (LT) and seasonal (day of year) dependences for the MSTID occurrence, horizontal velocity and period.

5. REAL-TIME MSTID MODEL

As it has been shown above, it has been demonstrated in previous works that the "linear" (or "larger scale") dependence of the differential ionospheric correction can be well addressed also in difficult scenarios (low latitude, Solar cycle maximum and distances of many hundreds of kilometres), by means of the tomographic (two-layer) ionospheric model (see Hernández-Pajares *et al.*, 1999, 2000, 2002, 2003, 2004). And the typical main remaining source of errors was the "non-linear" (or "shorter scale") contribution from Medium Scale Travelling Ionospheric Disturbances, MSTIDs. Hence the real-time modelling of the MSTID effect on precise GNSS navigation (using RTK, VRS, TCAR or WARTK techniques among others) has the potential of increasing the corresponding Service Areas, because in this way the differential ionospheric correction computed by the user can be even

Table 1.- Summary of MSTID parameters estimated from different local networks during 2002-2003. They can be considered the definition of the "Differential Delay Mitigation Model for MSTIDs" (DMTID) through a simple planar wave model. The particular parameters corresponding to the analyzed experiment are also included. (Remarks: * Day of year in North Hemisphere, day of year + 183 days (modulus 366) in South Hemisphere; ** Azimuth referred to the north, clockwise in North Hemisphere, and referred to the south, anticlockwise in South Hemisphere; *** The period is indicated just for information purposes -not strictly needed in DMTID-). The last column corresponds to the adopted values for the analyzed experiment (February 17th, 2005).

Local season	In Winter	In Summer	Adopted value in the experiment
Days* of year	270-366 001-110	130-290	048
Local Time / hours	0700-1800	1800-2400 0000-0400	0700-1800
Velocity / m/s	150-250	80-140	200
Azimuth** / degrees	130-200	200-300	180
Period*** / seconds	900-1100	800-1200	1000

more accurate, helping on fixing carrier phase ambiguities at even larger baselines, with the corresponding precise navigation with errors below 10 centimeters.

In this context, a new simple model is proposed to improve the precise GNSS navigation performance significantly: it is the so called "real-time differential delay model for mitigating MSTIDs" (hereinafter DMTID). It consists of applying a planar wave MSTID horizontal propagation model, taking into account the propagation parameters given by the seasonal behavior shown in HJS06, and summarized in the last section. From this simple model, a MSTID differential delay (Δt) is computed for each given satellite between the roving user and reference receiver ionospheric pierce points (dark and bright dots in Figure 6, respectively). In this case, the reference receiver should be the closer one experiencing the MSTID before the user, taking into account the typical MSTID velocity azimuth (poleward in local winter/day time and eastward in local summer/night time). Such receiver will be named as the "precursor reference site" (PRS).

Indeed, in this way, the buffered values of MSTID state for the chosen reference receiver, conveniently stored by the user, can be used as predictor of its pierce point

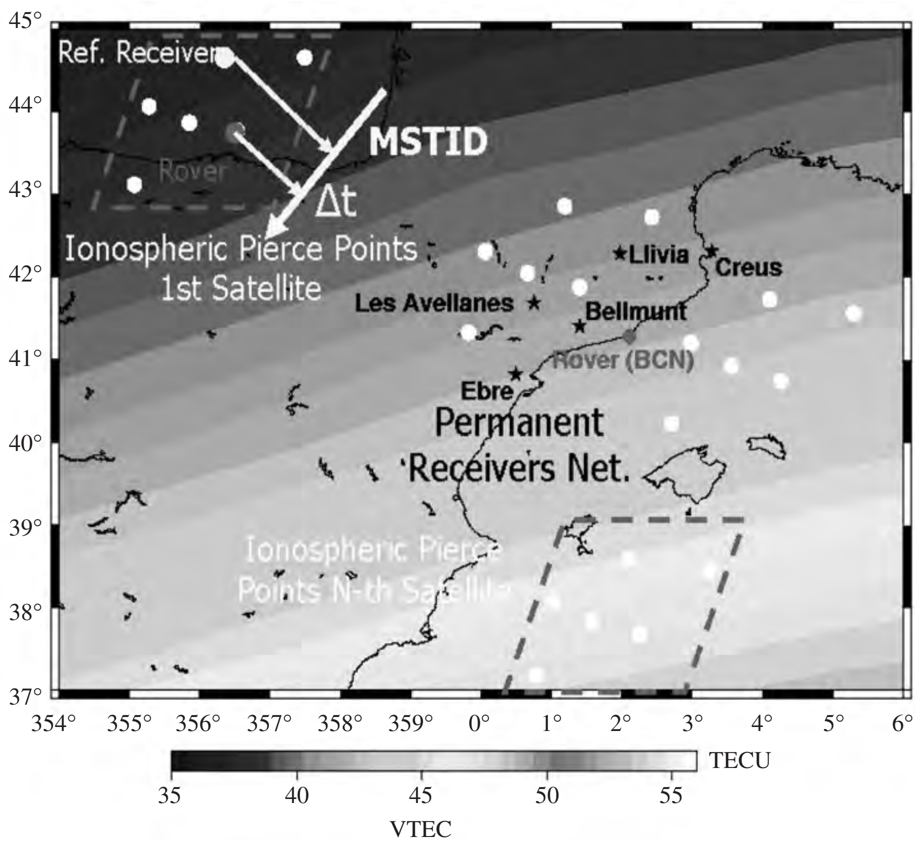

Figure 6.- Layout supporting the MSTID real-time model description.

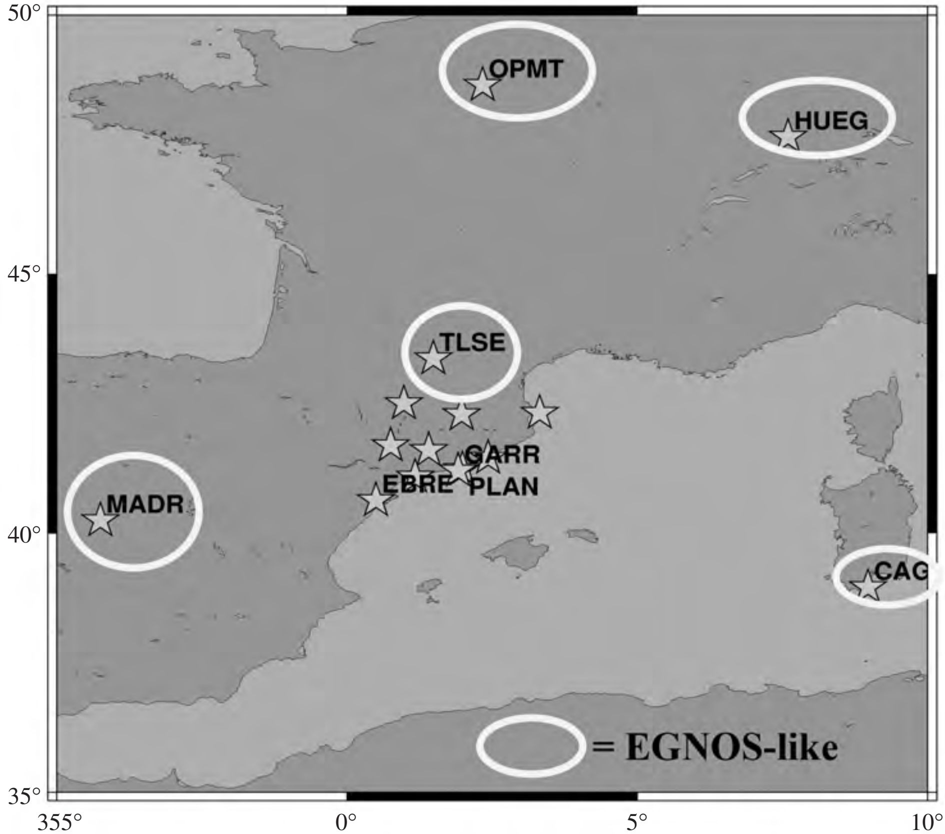

Figure 7.- Map indicating the reference receivers: encircled for large network and the remaining labelled ones for small network; the remaining receivers (non-labeled) are treated as roving users.

state, applying the temporal delay Δt (see Figure 6). In which way such MSTID states can be estimated in real-time? Firstly the broadcasted ionospheric corrections will be considered, corresponding to the cluster of pierce points associated with the observation of each given satellite from the local, regional or wide area network of permanent GNSS receivers, used to compute them. Secondly, such values are adjusted at each given updating epoch under a linear or quadratic model –depending on the baselines lengths-. Such adjustment performs a sort of spatial detrending of the TEC variation in the corresponding ionospheric region (see Figure 6). Hence the corresponding residuals, which can be broadcasted to the users as well, can be interpreted as the MSTID state estimations affecting the satellite measurements observed from each permanent receiver. But in fact, as mentioned above, the user should store, in real-time, such residuals corresponding to the "precursor" reference site only, PRS, during a typical time, for instance, up to Δt~100 km / 200 m/s = 500 seconds or more, for a baseline user-precursor reference site of 100 km under local winter / daytime MSTIDs.

It is important to say that the above mentioned delay Δt to be applied to the PRS MSTID states (per-satellite adjustment series), before subtracting it from the ionospheric correction provided to the rover, should take into account the pierce point Doppler effect, due to the relative movement of the pierce points, as done in HJS06 -see equation (6)-.

One last comment regarding this point is that applying such delay to a satellite not affected by any MSTID should not be a problem because usually the PRS would know that (for instance using the SRTI index). Otherwise this would not be an issue either, since the residual (MSTID state) should be a small random factor in such a case.

6. APPLICATION TO WIDE AREA RTK

In order to test the performance of the real-time MSTID model, DMTID, 5 IGS permanent receivers have been selected in West Europe (circled points in Figure 7), with typical distances between them of 500 km or more, acting as reference sites. In this way, it is possible to emulate a real-time Wide Area RTK Central Processing Facility (WARTK-CPF, see Hernández-Pajares *et al.*, 2004 for details). Nine additional permanent receivers, belonging to real-time CATNET network in Catalonia, at NE Spain (Talaya and Bosch, 1999), were treated as rovers, emulating the real-time positioning with WARTK corrections broadcasted from the CPF. Additionally, the CATNET receivers EBRE, GARR and PLAN were used as well as references in a second independent configuration. In this way, we have been able to test the DMTID performance for 14 different baselines ranging from 10 to more than 300 kilometers to the nearest reference site.

This test has been performed with data gathered during day 048 of 2005 (February 17th), coinciding with the SIS-2 EGNOS campaign. Hence, this corresponds to a winter day, and according to the previous study (see Table 1), it constitutes the worst case scenario, from the point of view of MSTID activity, expected at noon time.

The following parameters have been selected for DMTID, taking into account the study summarized in the previous section: southward planar waves moving at 200 m/s with a period of 1000 seconds, acting from 0700 to 1800LT (see again Table 1). Such parameters, obtained from analyzing data coming from 2002-2003 datasets of different local networks worldwide distributed, are quite compatible with the actual ones, computed only for checking purposes from a subset of the data used in the experiment (see Figure 7), as it can be seen in Figure 8 and Figure 9. In the first figure, the Single Receiver TID Index (SRTI) computed from EBRE data can be seen. SRTI is basically the second order derivative of the ionospheric carrier phase combination for a given satellite-receiver temporal series (see details in HJS06). Such plot confirms the prediction of MSTIDs occurrence in the day time, as it corresponds to a winter day. And the propagation parameters derived from the network are well represented by the selected parameters as well (see Figure 9 and Table 1).

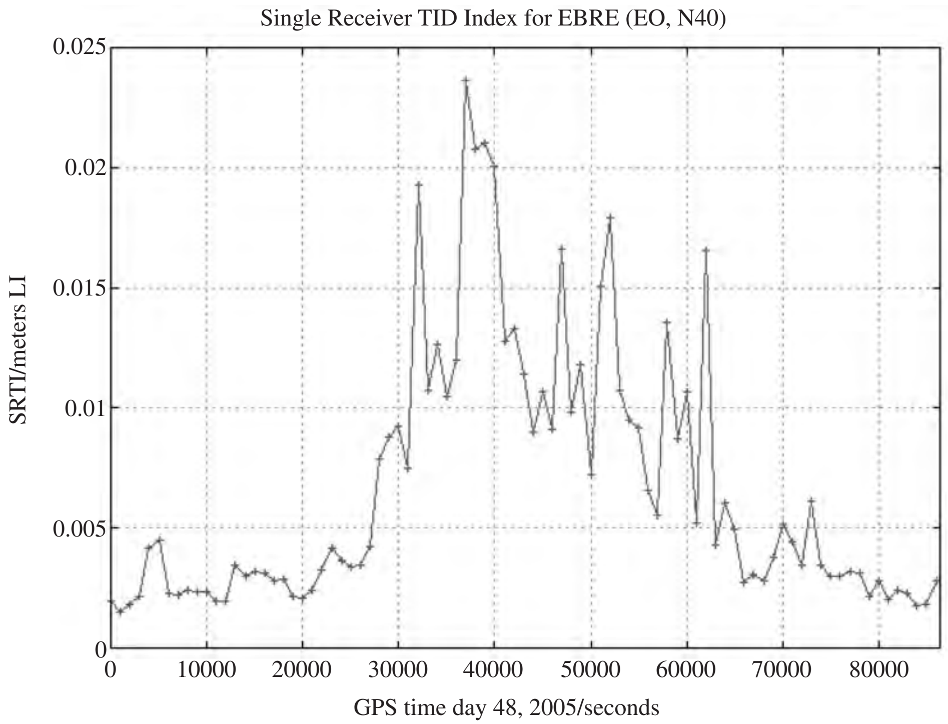

Figure 8.- Single Receiver TID Index computed for receiver EBRE, in terms of GPS time, for day 48 of 2005.

In order to show the DMTID performance, we will mostly concentrate on the representative case of receiver LLIV treated as rover at more than 100 km from the nearest reference site, TLSE (see Figure 7).

The typical results obtained at the ionospheric corrections show that the MSTID model correction (DMTID) tracks the actual ionospheric perturbations better, compared with a simple local or broader lineal adjustment.

It can be also seen the correlation between the ionospheric error and the corresponding SRTI index (Figure 8), as it could be expected from the above commented previous studies (Figure 3). And more important: it can be seen that the DMTID impact on the ionospheric error reduction can reach up to 50% or more in some epochs.

The impact of DMTID on the roving user ambiguities fixing in the WARTK scenario (Hernández-Pajares *et al.*, 2000) produces a well maintained ambiguity fixing rate over the 80%, also in moments of high MSTID activity. This is not the case when such model is applied under just a local or more general linear fitting, going down to less than 40% of ambiguity fixing rate without applying the DMTID.

Moving towards the final target, the real-time positioning, the corresponding navigation improvement leads to about 10 cm of RMS in front of about 20 cm not using DMTID, in both cases for the vertical coordinate error, the more affected one

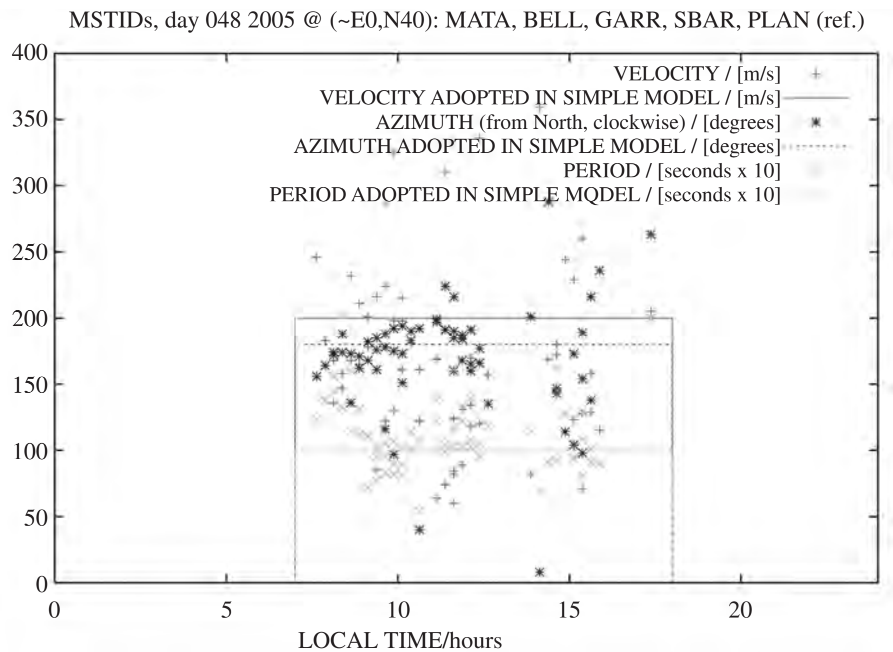

Figure 9.- Plot showing the compatibility of the actual and modeled MSTID characteristics (DMTID) during the experiment analyzed in this paper (day 048, 2005). The adopted values in the experiment, shown in Table 1, are also represented in the plot (velocity, azimuth and periods of 200 m/s, 180 deg and 1000 seconds, since 0700 to 1800 LT).

by the ionospheric errors. Additional improvements in the epochs with higher MSTID rates are foreseen with the use of dedicated local network (in the east-poleward part of the reference receiver network) to provide real-time user MSTID precursors in a more accurate manner.

Finally, the increase of WARTK service area under such difficult scenario can be seen in Figure 10, taking as reference a daily averaged error given by the threshold of 0.25 TECU (see line). It can be seen that the corresponding baseline distance increase, given by DMTID, goes from 110 or 180 km under plain or MSTID downweighted WARTK respectively, up to about 250 km with the new approach, from the nearest reference site. This means an increase of about 40% in distance, and about doubling the service area. This improvement is also significant for shorter baselines (typical of RTK for instance) with an improvement of more than 20% for baselines below 50 km (see same figure).

These results make feasible the improvement of existing GNSS applications, and the supporting to new ones, such as subdecimeter-error-level navigation at continental scales (see for instance Hernández-Pajares *et al*., 2000, 2002, 2003), instantaneous GPS meteorology (Hernández-Pajares *et al*., 2001), single-antenna user orientation (Hernández-Pajares *et al*., 2004), deep-sea precise navigation and Tsunami monitoring (Colombo *et al*., 2005), among others.

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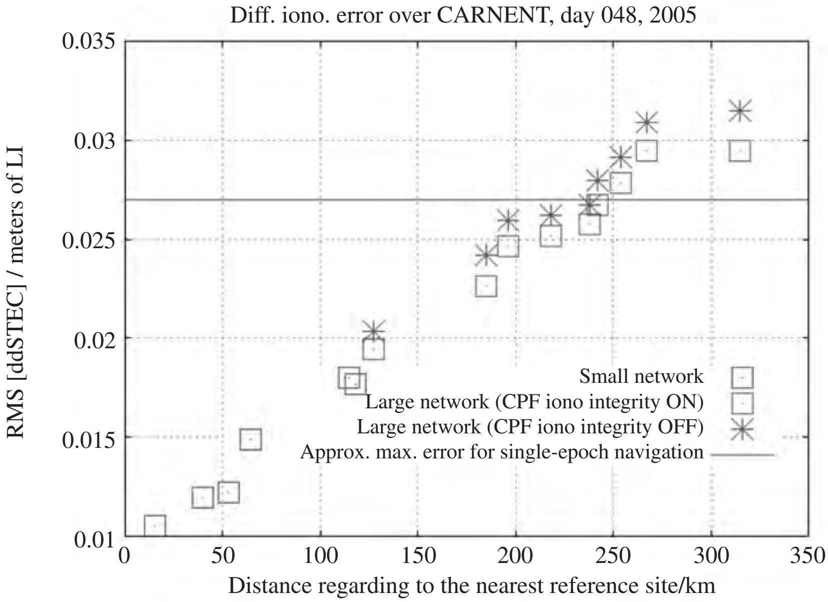

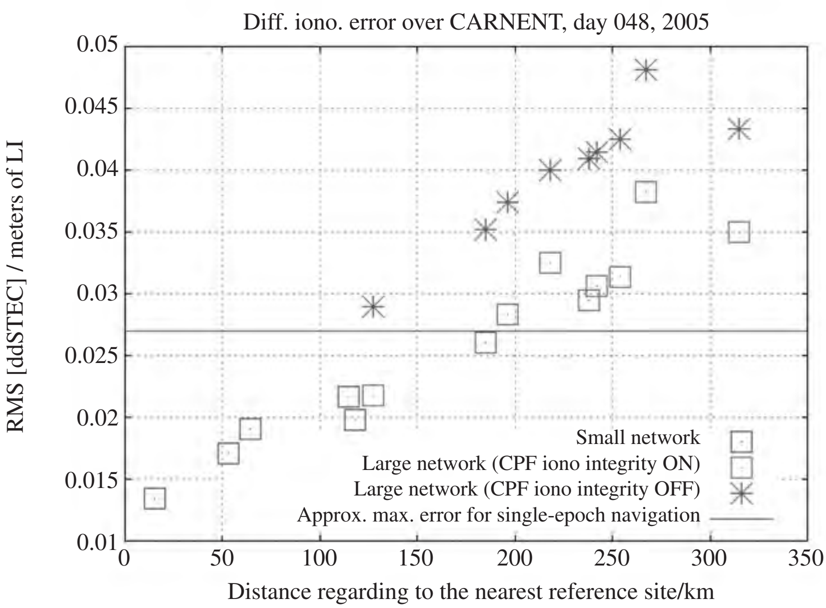

Figure 10.- Real-time WARTK correction error –in meters- in terms of baseline length –in kilometers- averaged during 24 hours: it can be seen in topside plot using the new real-time MSTID modelling (DMTID) with and without downweighting (similar results), and just using the linear interpolation in the bottom side plot, (with and without satellite downweighting in function of its MSTID affection as well). The reference ionospheric error threshold of 2.7 cm (0.25 TECU) is also indicated as a line, coinciding approximately with the ability of real-time ambiguity fixing for about 2/3 of the observed satellites (1-sigma in an assumed Gaussian distribution).

7. CONCLUSIONS

This works has a main motivation, the WARTK technique, which allows, from an optimal and accurate real-time modelling of both mid-large scale ionospheric structures and geodetic dependences, to provide subdecimeter-error-level navigation services, supported by Wide Area permanent networks of GNSS receivers, such as those supporting SBAS systems (EGNOS, WAAS...). In this context, this paper has studied the small scale ionospheric variability, in which the repeatability of MSTIDs characteristics opens the door to simple ways of mitigation, by simple real-time modelling from the reference receiver observables themselves. We have shown the performance of this approach, in one of the worst scenarios, in winter daytime and in wide-area networks, with typical distances between reference sites of hundreds of km. Our starting point was the last version WARTK technique, as was defined and tested in Hernández-Pajares *et al*., 2004. Nevertheless, this new MSTID simple model can also improve results with other techniques of carrier-phase based GNSS navigation (such as RTK, VRS and TCAR).

8. ACKNOWLEDGEMENTS

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