New potential applications for WADGNSS networks: precise navigation and meteorology

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ABSTRACT

The decorrelation of the ionospheric corrections at distances of hundreds km, like in the WADGNSS networks, is the main reason that impedes the real-time carrier phase ambiguity resolution in the reference stations and in the GNSS users receivers. In this paper the authors report the successful real-time carrier phase ambiguity determination for both reference and user receivers in WADGNSS-like networks, based on the precise real-time determination of the double differenced ionospheric corrections (between pairs of stations and satellites). Several experiments have been performed in different ionospheric conditions. And as a direct consequence, precise real-time positioning and real-time zenith tropospheric delay (ZTD) determination can be also obtained, with errors better than 10 cm for the navigation and about 1 cm for ZTD. These results strongly suggest the feasibility of providing additional real-time services to the existing and planned WADGNSS networks, like WAAS, EGNOS and MSAS.

INTRODUCTION

As it is known, in wide-area navigation augmentation systems (WAAS, EGNOS..., see for example [1]) the ionospheric corrections have to be calculated from stations typically separated several hundreds km or more, with only the data gathered until the present epoch. This limitation usually produces worst results than computing the ionospheric corrections in post-process. One way to overcome this natural limitation is to run also, simultaneously, a geodetic program solving the carrier phase biases, in particular for a network of reference stations with accurate coordinates. Combining both complementary types of information, the ionospheric corrections and also the geodetic outputs can improve significantly. Some examples of that can be found in [2] for ionospheric corrections, in [3] for navigation and in [4] for real-time tropospheric determination.

The purpose of this paper is to show the feasibility of the synergy between precise ionospheric modeling, with the benefits of a tomographic approach, and precise position determination, in real-time, and using reference GNSS stations separated by hundreds of kilometers. This includes Wide Area Differential GNSS (WADGNSS)-like networks, for example WAAS, EGNOS or MSAS, in which this combination of techniques makes feasible, for example, On-The-Fly ambiguity resolution for roving receivers (left hand plot of figure 1, and details in [3]) with position accuracies below 10 cm, or the real-time tropospheric estimation (right hand plot of figure 1, and details in [4]).

The paper is organized as follows: The first part includes the description of the technique, and a table reporting a summary of the experiments performed until now to test this strategy, in different WADGNSS-like scenarios. In the second part of the paper, two new studies are presented in detail, improving the availability of the precise ionospheric corrections. The first one shows the effectivness of the technique in resolving ambiguities on the fly in the presence of local ionospheric irregularities, such as Traveling Ionospheric Disturbances (TID's). This first experiment was performed in 1999, with the rover at distances of more than one hundred kilometers from the nearest reference receivers, and at high northern latitudes. The second experiment has been performed in 2001 at mid latitudes, close to the 2000 Solar Maximum, and hence with high levels of ionospheric refraction. An additional difficulty that makes this scenario interesting is that the roving receiver has been set up in a fisher ship, navigating then in the outer perimeter of a reference network with few stations, used to compute the real-time ionospheric corrections.

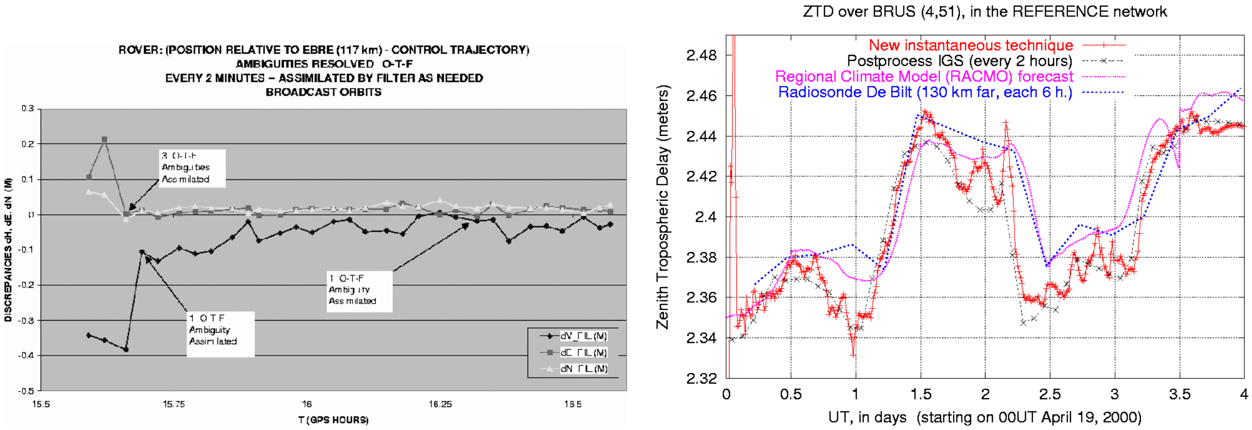


Figure 1: Two recent applications of the capability to solve in real-time the double-differenced carrier-phase ambiguities by means of the real-time ionospheric corrections computed using the WARTK technique described in the paper: In the left hand plot, the errors in the navigation of a rover (a car in this case) are less than 10 cm in the three components -North, East and Up- (experiment "Bellkin'99", in table 1). The right hand plot shows the difference between the real-time vertical tropospheric delay and (a) the IGS combined post-processed, (b) radiosonde measurements and (c) numerical weather model predictions. The errors are typically less than 1cm (experiment "SolarMax-1", No.4 in table 1).

DESCRIPTION OF THE TECHNIQUE

The free electron ionospheric distribution is approximated by a grid of voxels in which the electron density is assumed constant at a given time in an Earth Centered Inertial (ECI) system (see a typical layout in figure 2). The ionospheric determination is performed solving in real-time, by means of a Kalman Filter ([5]), the mean electron density N_e of each illuminated cell i,j,k (in solar longitude, latitude and height respectively), treated as a random walk process, and with typical process noise of 10^9-10^{10} electrons/m^3/$\sqrt{hour}$. The carrier phase data are the only ones used. Then the pseudorange code noise and multipath are avoided. The carrier phase biases B_I (constant in each given continuous arch of carrier phase data for each satellite-receiver pair) are estimated simultaneously as random variables (that become white noise random processes when a cycle-slip happens). In the filter the biases decorrelate in real-time from the electron density values, as far as the satellite geometry changes and the variance of both kind of unknowns became smaller (see equation 1 that represent the model for a given ionospheric datum, between one GNSS satellite and one receiver, being L_1 and L_2 the carrier phases in length units, L_I=L_1–L_2 and N_e the electron density).

$$L_I = STEC + B_I = \int_{REC}^{SAT} N_e dl + B_I = \sum_i \sum_j \sum_k (N_e)_{i,j,k} \Delta s_{i,j,k} + B_I \quad (1)$$

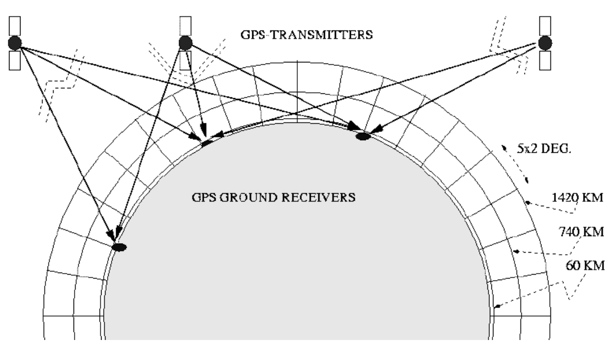
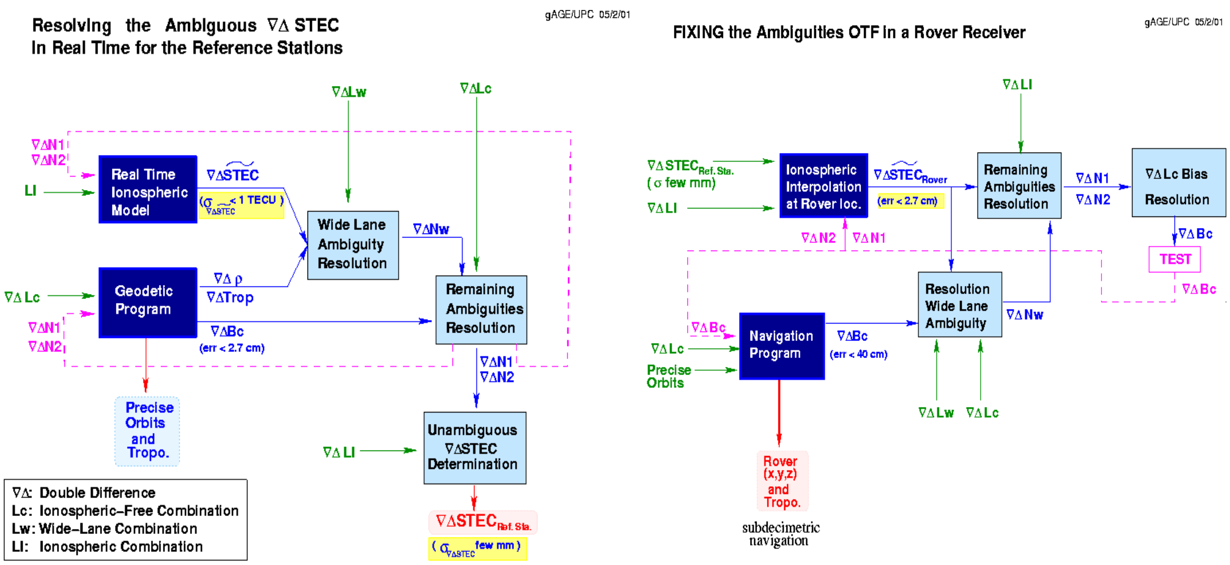


Figure 2: Meridian slice of the voxels in which the ionospheric electron density distribution is decomposed, in the GNSS data driven real-time model, equation 1.

This approach is suitable in particular to detect local features of the electron density distribution, and the use of two layers with ground GNSS data –instead of one layer– reduces significantly the mismodelling of the electron content determination ([6],[7]) In the case of WADGNSS networks, from these real-time slant total electron content (STEC) corrections obtained by equation 1, it is possible: Firstly (see flow chart in figure 3), to form the station-satellite double differences, $\nabla\Delta STEC$, and to obtain a second ambiguity (the widelane) in the reference stations, and, secondly (see flow chart in figure 4), to interpolate to the rover the resulting unambiguous LI in the reference stations, i.e. to provide to the roving receiver a very precise $\nabla\Delta STEC$ to the level of few tenths of TECU[1]. If the interpolated value is better than 2.7 cm ≅ 0.25 TECU, then the rover will be able to solve both ambiguities in real-time. This and another details of the technique, hereinafter Wide Area Real Time Kinematics (WARTK), can be found for instance in [8] and [2].



Figures 4 and 5: Flow diagram of the main processing steps for the reference net (left) and the roving receiver (right).

The results obtained so far with the WARTK technique, in different experiments, are summarized in table 1.

No.	Exp.	Ionos. Activity	Dist. (km) Rover/Ref.	Ref. Succes	Rover Success	Kind Rover	Dates	Region	Reported in
1	BelKin99	Quiet	116/ 286	97%	80- 100%	Car	March 23, 1999	Spain NE	Colombo et al. 1999
2	NWPacific (1)	Active Kp=6	400/ 900	90- 100%	80%	IGS Site	May 3, 1998	Canada -USA NW	Hernández-P. et al. 2000a Colombo et al. 2000
3	NWPacific (2)	Irreg. Apr30	162/ 900	95- 100%	80- 90%	IGS Site	Apr28 to May 1, 1998	Canada -USA NW	Hernández-P. et al. 2000b
4	SolarMax (1)	Solar Max.	130/ 500	85- 95%	80%	IGS Site	Apr 19 -22, 2000	Central Europe	Hernández-P. et al. 2001
5	SolarMax (2)	Very Active	130/ 500	50- 95%	80%	IGS Site	Jul 12 -15, 2000	Central Europe	Hernández-P. et al. 2000b
6	Baltic99 (1)	TID's	144/ 285	97%	83%	Fixed Airplane	Aug 25, 1999	North Europe	This paper
7	Equator01	S.Max. Equat. Kp:0-9	1000- 3000	90%	-	IGS Site	Mar6 to Apr 2, 2001	Asia- Oceania	Hernández-P.et al.2001b
8	Lavi2001	S.Max	150/280	90%	65%	Fisher Boat	June 20, 2001	NE Spain	This paper

Table 1: Summary of the experiments performed so far to quantify the performance of the real-time tomographic model of the ionosphere and the associated WARTK technique. More details can be found in the references indicated in the last column.

For the kinematic use of the algorithm one of the strongest limits is the existence of local ionospheric irregularities, such as Traveling Ionospheric Disturbances (TID), that can produce poor results using a linear interpolation of the ionospheric corrections between the reference stations. We will improve the performance incorporating the rover dual frequency data ([2]). These additional data will be also helpful when the roving receiver has to navigate in the perimeter of a reference network with few stations, such as in the case of the second experiment analyzed in detail in this work.

[1] 1 TECU = 10^{16} electrons/m^2 ≅ 10 cm in LI ≅ 15 cm in L_1 ≅ 20 cm in Lw (widelane combination).

EXPERIMENT (BALTIC'99): ROVER ALGORITHM WITH TRAVELING IONOSPHERIC DISTURBANCES

The purpose of this experiment is to show the performance of the WARTK algorithm, especially in the interpolation of the precise $\nabla\Delta STEC$ from the reference stations to the rover in the presence of local ionospheric irregularities.

DATA DESCRIPTION

The data were collected at seven fixed dual-frequency GPS receivers in the Baltic Sea region, in August 25th 1999, from 06 to 11 hours UT. The seven included IGS stations VIS0, MAR6, VIRO and LAMA (recording each 30 sec.), and the fixed stations TUOR, HIIU and MHN2 (recording each 1 sec.), as part of a remote-sensing flight with onboard GPS receivers. In what follows, the fixed receiver MHN2 is treated as rover and, as it can be seen in the corresponding map, figure 5, the typical distances between the reference receivers are 200-400 km, and between the rover and the closest receivers are 150-200 km.

DISCUSSION AND RESULTS

From previous studies (experiments 2 and 3 in table 1), the resolution of the reference stations ambiguities normally should not be a problem in this scenario, at high latitude and low geomagnetic activity (a success close to 100% of the attempts made at every epoch to resolve the ambiguities is attained).

But the situation is complicated, in the interpolation process, by the occurrence of Traveling Ionospheric Disturbances (TID's) affecting the signals of most of the GPS satellites observed during the flight. An example of the observed ambiguous STEC (L_I) for satellite PRN25 is shown in the first plot of figure 6. Oscillations reaching 20 cm can be observed with different intensity and relative phase depending on the observer's position, and hence depending on the station. An example of the direct impact of these TID's in the $\nabla\Delta STEC$ interpolation to the rover can be also seen in figure 6, second plot. The linear interpolation between the three surrounding reference stations MAR6, HIIU and TUOR -the reference for the double differences- (see map in figure 5) produces errors greater than 2.7 cm compared to the true $\nabla\Delta STEC$ as observed at the rover. An error of that size causes one or more cycles of error in both the L_1 and L_2 ambiguities of the rover. When the dual-frequency data of the rover receiver, MHN2, are also used in the WARTK technique, as it is indicated in figure 4, the results are significantly better, with errors typically below 2.7 cm.

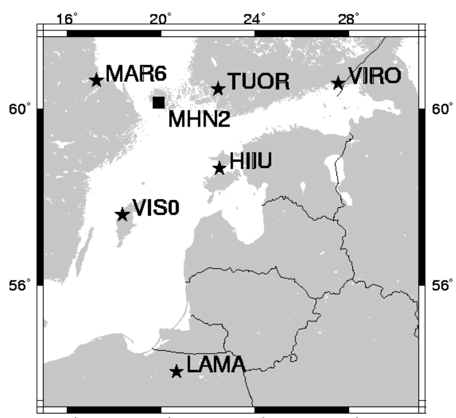


Figure 5: Map with the fixed reference stations (stars) and the fixed station MHN2 treated as rover (square), used in the experiment in which the ionosphere presents TID's (August 24, 1999).

An overall picture of the performance for all the satellites can be seen in figure 7, in which the errors in $\nabla\Delta STEC$, and corresponding success rate in full (L_1 and L_2) ambiguity resolution for the rover are plotted, with an overall success of 83% of attempts made at all epochs. However, linear interpolation (see the same plot) gives just a 49% of success in this scenario.

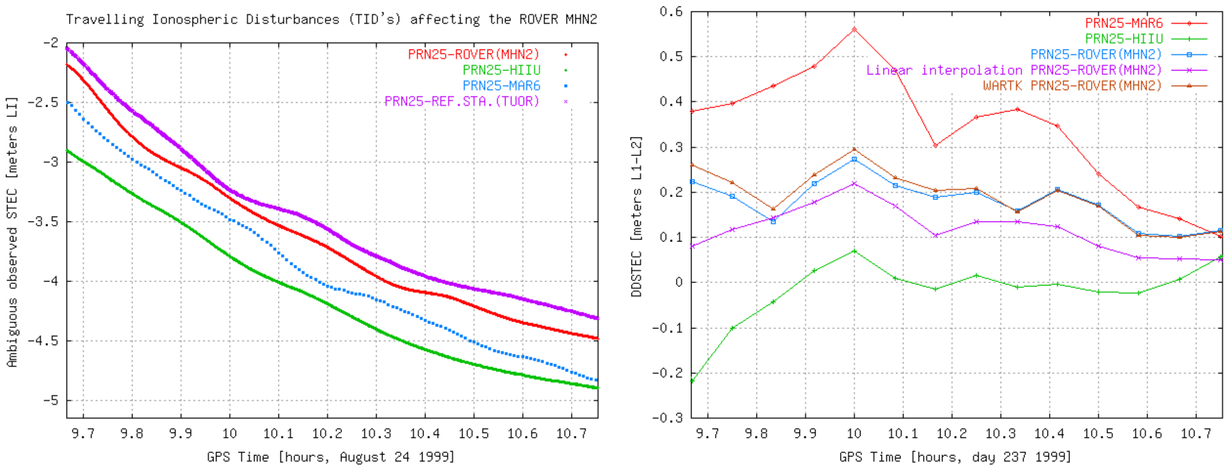


Figure 6: Example of TID's observed in satellite PRN25, from the rover station (MHN2), and the reference stations MAR6, HIIU and TUOR (the reference for the double differences). In the left hand figure the ambiguous STEC's are plotted, in which the propagation of the TID's can be observed. And in the right hand figure, we can see the TID's impact on the double differences, as they affect the performance of the linear interpolation done to provide $\nabla\Delta STEC$ corrections to the user. The TID's affected more than 50% of the GPS satellites measured in this experiment.

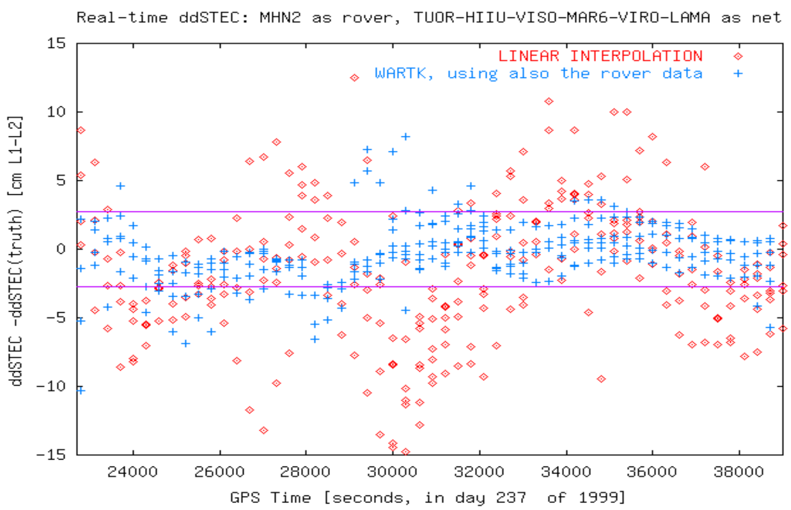


Figure 7: Error of the double differenced STEC for the fixed site MHN2, treated as rover, in function on the time, using the WARTK technique (blue crosses). The overall performance is the 83% of success (regarding on all the available satellites) in providing an ionospheric correction precise enough to determine the two rover carrier phase ambiguities (i.e. better than 2.7 cm). When an alternative linear interpolation method is used (errors in red diamonds), the success decreases to 49%. The corresponding performance for one-cycle of maximum common error in both ambiguities of L1 and L2 is 99% for WARTK and 92% for linear interpolation.

EXPERIMENT (L'AVI-2001): FEW REFERENCE STATIONS AND CLOSE TO SOLAR MAXIMUM

As it has been commented above, the main goal of this new experiment is to show the performance of the WARTK technique when few reference stations are used, coinciding with high ionospheric refraction values corresponding to the high level part of the Solar cycle.

DATA DESCRIPTION

The experiment was performed during 21 June 2001, close to the recent Solar Maximum, involving two GPS receivers (Ashtech Z-XII and Trimble 4000-SSI) on board a fisher ship (named "L'Avi"), in the North-East Mediterranean coast around Barcelona (Spain). The permanent reference receivers EBRE (the reference for the double differences, 157 kilometers far) and CREU, 138 kilometers far, have been used for computing the real-time ionospheric corrections. And an additional GPS receiver at a fixed site close to the ship trajectory –with well known "truth" ambiguities computed in postprocess- has been also treated as rover (INDR). The fixed sites and the ship trajectory can be seen in the map, and zoom, shown in figure 8).

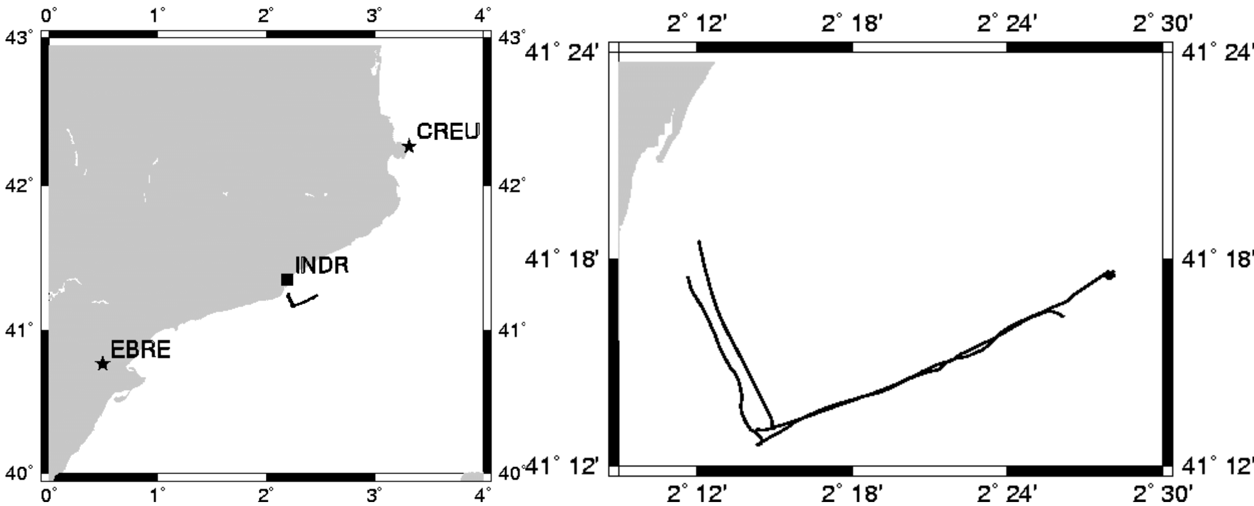


Figure 8: Map with the fixed reference stations (stars) and the fixed station INDR treated as rover (square), used in the experiment L'Avi2001, in ionospheric conditions close to Solar Maximum, and with few reference stations, only EBRE and CREU (left). The detail of the fisher ship trajectory computed from the GPS data is also represented on the right hand (June 20, 2001, 0400 to 1400 LT approximately).

DISCUSSION AND RESULTS

From a practical point of view it can be interesting to know which is the performance of the new techniques, such as WARTK, with few reference stations. In these scenarios some "prons" and "cons" are that it would be more simple to implement the new procedures, but the accuracy of the corrections is affected by the limited information. In order to test the performance of WARTK in these scenarios, we have selected two small reference networks: (1) With both CREU and EBRE (138 and 157 km far, respectively, from the rover receivers), and (2) with just EBRE, not allowing this single station net configuration to improve the solution by fixing ambiguities (figure 4). The real-time double differenced STEC computed for INDR are compared respectively, in figures 9, left and right hand plot, with the truth values, precise to the mm level after being solved in postprocess fixing ambiguities. It can be seen that, still being the performance with two reference sites better (about 66%), the performance is still aceptable with just only one reference receiver, i.e. such in the case of the "classical" RTK computations (with a 57% of success), allowing practically a full navigation with a mean of about 3-4 pairs of integer ambiguities exactly known at each given epoch, once ambiguity validation procedures are applied with the help of the geodetic program. When the tolerance is increased to an error of +/- 1 cycle in both ambiguities, then percentages greater than 90% are attained with both nets, with two and only one reference site.

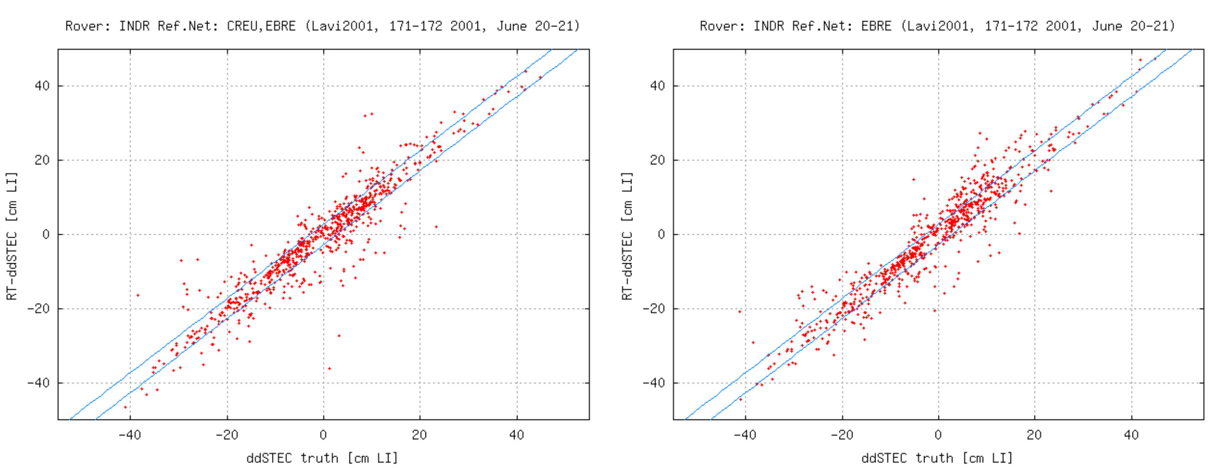


Figure 9: Real time double differenced STEC versus the truth value --computed in postprocess--, for the fixed site INDR treated as roving receiver using both EBRE and CREU fixed sites to compute the ionospheric corrections (66% of success, left plot), and just only EBRE as reference site (57 % of success, right hand plot). The band limited by the blue lines corresponds to the values for which the ionospheric correction errors (below 0.25 TECU = 2.7 cm LI approx.) are low enough to compute both integer ambiguities without error, in L1 and L2.

These results can be easily translated also to the real roving receiver, at the fisher ship L'Avi, due to the proximity with INDR.

An additional criterium, compatible with the capability to solve exactly both carrier phase ambiguities (necessary, but not sufficient condition), is to check the stability of the real-time double differenced BI biases, computed with the ionospheric model (equation 1). It can be seen in figure 10 that most of them are stable to a level compatible with the resolubility of both ambiguities (2.7 cm in LI = 0.25 TECU) both at the fixed site INDR, treated as rover (86%, left hand plot of figure 10, corresponding to the results with two reference stations), and at the real roving receiver LAVI onboard the fisher ship (78%, right plot of figure 10).

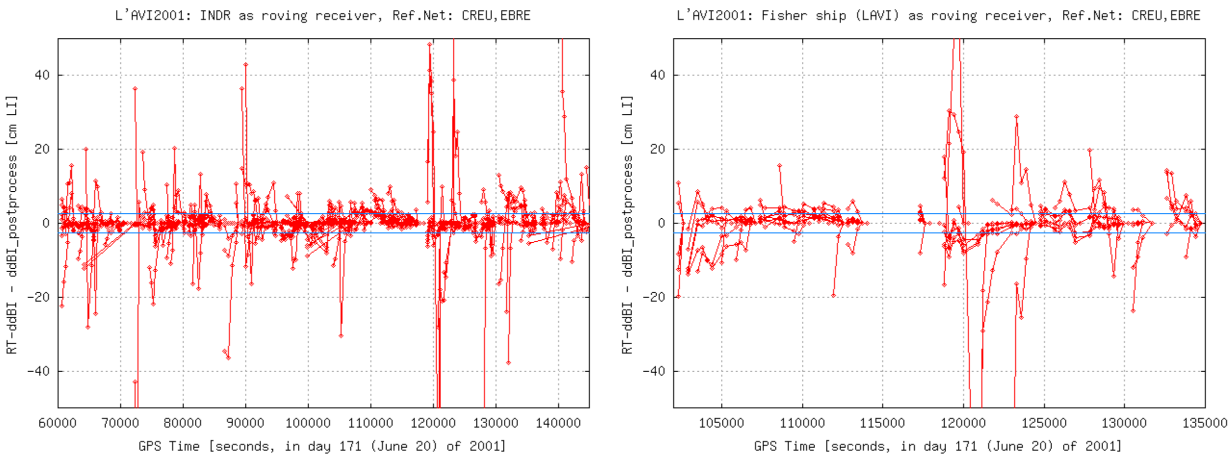


Figure 10: Double differences of the ionospheric free carrier phase biases (BI), referred to the final value of each continuous arch of carrier phase data (red points, connected with lines whithin each arch): fixed site INDR treated as rover (left hand plot) and real roving receiver LAVI onboard the fisher ship (right plot). The tolerance band of variation (+/- 2.7 cm), compatible with the capability to solve both carrier phase ambiguities in real-time, is also delimited by the horizontal lines (83% and 78% of BI determination whithin the tolerance band, for INDR and LAVI respectively).

SUMMARY AND CONCLUSIONS

The Wide Area Real Time Kinematic (WARTK) algorithm performs well when used to compute precise real-time ionospheric corrections in WADGPS-like networks. In several experiments previously reported in other publications, the WARTK provided $\nabla\Delta STEC$ better than 2.7 cm (1/4 TECU) for the reference and rover receivers, in middle and high latitudes, and under different ionospheric conditions.

The more challenging part of the technique, the interpolation of the precise $\nabla\Delta STEC$ from the reference stations to the rover, has been successfully tested in this paper in a difficult situation, with strong local irregularities in the ionosphere (TID's), while nevertheless doubling the performance compared to a standard linear interpolation technique (success of 83% vs 49%, respectively).

The performance of the real-time ionospheric corrections have been also tested in an additional difficult scenario: few reference stations (two, and only one) separated more than 100 km from the rover, and in the high part of the Solar Cycle with relatively high ionospheric refraction values. The results show the feasibility of solving both carrier phase ambiguities at real time, still with such limited ionospheric information, with a percentage high enough (66%) to help on precise navigation and in real-time meteorology in WADGNSS scenarios following respectively the strategies detailed in [8] and [4].

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References

[1] Hansen A.J., T.F. Walter, P. Enge, Real-time Ionospheric Tomography Using Terrestrial GPS Sensors, Global Positioning System, Selected Papers on Satellite Based Augmentation Systems (SBASs), Vol. VI, The Institute of Navigation, Alexandria, USA, 1999.

[2] Hernández-Pajares, M., J.M. Juan, J. Sanz, O. Colombo, H. Van der Marel, Real-time integrated water vapor determination using OTF carrier-phase ambiguity resolution in WADGPS networks, ION GPS'2000, Salt Lake City, September 2000b.

[3] Colombo, O.L., M. Hernández-Pajares, J.M. Juan, J. Sanz and J. Talaya, Resolving carrier-phase ambiguities on-the fly, at more than 100 km from nearest site, with the help of ionospheric tomography, ION GPS'99, Nashville, USA, September 1999.

[4] Hernández-Pajares, M., J.M. Juan, J. Sanz, O.L. Colombo, and H. van der Marel, A new strategy for real-time Integrated Water Vapour determination in WADGPS networks, Geophysical Research Letters, 28, 3267-3270, 2001.

[5] Bierman, G.J., Factorization Methods for Discrete Sequential Estimation, Vol. 128 in Mathematics in Science and Engineering, Academic Press, New York, 1977.

[6] Hernández-Pajares M., J.M. Juan and J. Sanz, New approaches in global ionospheric determination using ground GPS data, Journal of Atmospheric and Solar Terrestrial Physics. Vol 61, 1237-1247, 1999a.

[7] Hernández-Pajares M., J.M. Juan, J. Sanz and O.L. Colombo, Precise ionospheric determination and its application to real-time GPS ambiguity resolution, Institute of Navigation ION GPS'99, Nashville, Tennessee, USA, September 1999b.

[8] Hernández-Pajares, M., J.M. Juan, J. Sanz and O.L. Colombo, Application of ionospheric tomography to real-time GPS carrier-phase ambiguities resolution, at scales of 400-1000 km, and with high geomagnetic activity, Geophysical Research Letters, 27, 2009-2012, 2000a.

[9] Colombo O.L., Hernández-Pajares M., Juan J.M. and Sanz J., Ionospheric Tomography Helps Resolve GPS Ambiguities On-the-Fly At Distances of Hundreds of Kilometers During High Geomagnetic Activity, Position Location and Navigation Symposium (PLANS 2000 IEEE conference), San Diego (USA), March 2000.

[10] Wessel, P. and Smith, W.H.F, New version of the Generic Mapping Tools released, EOS transactions AGU 76, 326, 1995.

[11] Webb, F.H. and J.F.Zumberge, And Introduction to GIPSY/OASIS-II, JPL/CALTECH, JPL D-11088, 1997.