Real-time integrated water vapor determination using OTF carrier-phase ambiguity resolution in WADGPS networks

M. Hernández-Pajares, J. M. Juan, J. Sanz, *group of Astronomy and Geomatics, Universitat Politècnica de Catalunya (gAGE/UPC), Barcelona, Spain*

O.L.Colombo, *USRA/NASA GSFC, Maryland, USA*

H. van der Marel, *Delft University of Technology, The Netherlands*

BIOGRAPHIES

Dr. Manuel Hernández-Pajares is an associate professor in the Department of Applied Mathematics and Telematics at the Universitat Politècnica de Catalunya. He is currently focused on the area of GPS inospheric tomography, GPS data processing algorithms, including neural networks, and radionavigation.

Dr. J. Miguel Juan Zornoza is an associate professor in the Department of Applied Physics at the Universitat Politècnica de Catalunya. His current research interest is in the area of GPS Ionospheric tomography, GPS data processing algorithms, and radionavigation.

Dr. Jaume Sanz Subirana is an associate professor in the Department of Applied Mathematics and Telematics at the Universitat Politècnica de Catalunya. His current research interest is in the area of GPS ionospheric tomography, GPS data processing algorithms, and radionavigation.

Dr. Oscar L. Colombo works on applications of space geodesy, including gravity field mapping, spacecraft orbit determination, and precise positioning by space techniques, mostly for the Space Geodesy Branch (Code 926) of NASA Goddard Space Flight Center. In recent years, he has developed and tested techniques for very long baseline kinematic GPS, in collaboration with groups in Australia, Denmark, Holland, and the USA.

Dr. Hans van der Marel is assistant professor in the department of Mathematical Geodesy and Positioning of the Delft University of Technology. In recent years, he has been working on the development of an active GPS reference system in the Netherlands. Currently, he is involved applications of permanent GPS networks for geodesy, surveying and meteorology.

ABSTRACT

A major issue in many applications of GPS is the real-time estimation of the Integrated Water Vapor (IWV). Several authors have developed strategies that estimate IWV, or equivalently Zenith Tropospheric Delays (ZTD), with a latency of one hour or more. These strategies require that data from a regional GPS network be processed in near real-time, using precise IGS orbits in combination with partial orbit relaxation.

It has been shown recently that in Wide Area Differential GPS (WADGPS) networks several hundred Km across, double-differenced carrier phase ambiguities can be computed on-the-fly, using a real-time tomographic model of the ionosphere obtained from the same GPS data. In this work we study how such ambiguity resolution can help determine in real-time, instantaneously, the ZTD for a WADGPS network, using only the broadcast ephemeris. This approach allows any user in the WADGPS area to easily get its own real-time precise ZTD determination, which can be converted to IWV using measurements of atmospheric pressure.

The comparison between the real-time strategy presented and the postprocessed approach shows a general agreement of about 1 cm in the ZTD in WADGPS scenarios, improving by about 30-40% the results obtained also in real-time but without fixing the carrier phase ambiguities, for both reference and rover receivers. These results are achieved or can be achieved not only in quiet ionospheric conditions, but also during ionospheric disturbances and Solar Maximum conditions. This is an important issue for the ionospheric modeling, which is a key element of the algorithm.

In coming years, data from ground and satellite-borne GPS receivers will help monitor the state of the atmosphere (mapping tropospheric IWV and ionospheric

TEC), to study weather, Earth-sun interactions, and climate change. Real-time ambiguity resolution can enhance not only present uses of wide area GPS networks, in navigation and surveying, but also creates new ones in the field of meteorology.

INTRODUCTION

In the recent years it has been demonstrated that the Global Positioning System (GPS) can provide reliable estimates of the Integrated Water Vapor (IWV) with a high availability and temporal resolution (see for example Bevis et al., 1992, Coster et al. 1997, van der Hoeven et al., 1998).

The relevancy of GPS-IWV determination to weather forecasting is increased when it is obtained as close as possible to real-time, in any case with a maximum latency of about 2 hours. But until now, one of the main difficulties to get such real-time IWV is the lack of availability and integrity of precise predicted orbits (Ge et al., 2000). This makes it necessary to simultaneously estimate the orbit parameters, jointly with the IWV, in a data window wide enough (usually up to 24 hours), to ensure a reliable final estimate. But this computational strategy implies usually latencies of one hour or more.

In this paper we show that it is possible to get precise IWV at the level of 1.5 Kg/m^2 (or equivalently a precise Zenith Tropospheric Delay -ZTD- with an accuracy of 1 cm or better)[1] estimated as a random walk process in real-time, instantaneously, based on the On the Fly (OTF) ambiguity resolution in networks with reference GPS stations at Wide Area Differential GPS (WADGPS) distances (several hundreds of km). This OTF ambiguity resolution can be done through the integration of a real-time tomographic model of the ionosphere with a real-time positioning strategy as was demonstrated in Colombo et al. 2000 and Hernandez-Pajares et al., 2000.[2]

The main benefits of fixing ambiguities OTF for the tropospheric determination are that the carrier phase observations can be treated as very precise pseudoranges, not just in double-differenced processing but also in absolute processing. This strategy diminishes: (1) the number of unknowns to be solved for (about 50%) and hence the computational load, and (2) the correlations between the estimated parameters. This is specially important in the context of the continuous forward-running filter used in WADGPS, in contrast with the data windows of several hours used in the near real-time strategies.

This approach allows also any passive user (i.e. rover receiver) to estimate in a precise way its ZTD, without increasing the reference network computation load. This opens the new possibility of easily deploying, in regions with WADGPS networks (like U.S.A. or Europe), an unlimited number of GPS receiver working as real-time (instantaneous) meteorological sensors.

The algorithm, which only use carrier-phase data, has two parts: one for the reference stations and one for the user (rover receivers). In the next two sections we will describe the algorithmn. Two measurement scenarios, with three different data sets, involving different ionospheric conditions, which include ionospheric disturbances, Solar Maximum peak and large geomagnetic storms, were used to proof the concept.

ALGORITHM: REFERENCE STATIONS

Following the procedure described in Colombo et al. 2000 and in Hernández-Pajares et al. 2000 for the OTF ambiguity resolution, a reference station network of GPS receivers with distances of several hundred km is considered.

This first issue is to fix OTF the double differenced ambiguity $\nabla\Delta N_\delta$ of the widelane combination of L_1 and L_2 carrier phases (L_δ, all in length units). We can exploit the fact that the coordinates of these stations are already known at cm level. This allows us to estimate orbit corrections and the L_c ionospheric-free carrier phase combination bias, B_c, with a sufficient precission of few centimeters.

Then the widelane ambiguity can be derived:

$$\lambda_\delta \nabla\Delta N_\delta = \nabla\Delta L_\delta - \nabla\Delta L_c + \nabla\Delta B_c - \nabla\Delta I_\delta \qquad (1)$$

$\nabla\Delta$ being the double difference (station-satellite) operator, $I_\delta = \alpha' \cdot STEC$ the ionospheric delay of the wide-lane combination, and α' a dimensional scale factor (approximately 20 cm/TECU, being 1 TECU=10^{16} e/m^2).

As the widelane wavelength is about 86 cm, and B_c can be determined at the level of a few cm at the reference stations, we need find in real-time the double differenced Slant Total Electron Content ($\nabla\Delta STEC$) with a standard deviation of 20 cm (i.e. 1 TECU) to ensure a 95% percent success rate. This can be fulfilled by means of a tomographic model obtained with only the network GPS carrier-phase data, as it is explained in Hernández-Pajares et al. 2000. The electron content is modeled by means of voxels (i, j, k) in a Sun-fixed reference frame, where the

[1] 1 Kg/m^2 IWV = 1 mm Integrated Precipitable Water Vapor (IPWV) 6.7 mm ZTD approximately.

[2] In Colombo et al., 1999, 2000, the tropospheric refraction was estimated in real-time mode to enhance the kinematic navigation solutions. In the present paper the quality of the real-time ZTD estimation is studied in detail.

electron density $(N_e)_{i,j,k}$ is considered constant inside each voxel in a given epoch. It can be treated as a random walk and estimated by means of the scalar filter approach (Biermann 1977), using the following measurement model,

$$\mathrm{L}_I = \mathrm{L}_1 - L_2 = \underbrace{\sum_i \sum_j \sum_k (N_e)_{i,j,k} \Delta s_{i,j,k}}_{\alpha\ STEC} + b \qquad (2)$$

where b is an unknown constant bias in each carrier phase shift between GPS transmitter and receiver, and α=10.5 cm/TECU.

Once $\nabla\Delta N_\delta$ is fixed (rounded to the closest integer, in this work), we can solve, fix and validate, again with the help of the precise B_c determination, the full set of ambiguities of L_1 and L_2, $\nabla\Delta N_1$ and $\nabla\Delta N_2$:

$$\begin{aligned} \nabla\Delta(N_1+N_2) &= NI[(2\nabla\Delta B_c - \lambda_\delta\, \nabla\Delta N_\delta)/\lambda_n] \\ \nabla\Delta N_1 &= 0.5[\nabla\Delta N_\delta + \nabla\Delta(N_1+N_2)] \qquad (3) \\ \nabla\Delta N_2 &= \nabla\Delta N_1 - \nabla\Delta N_\delta \end{aligned}$$

being $\lambda_n = c/(f_1+f_2)$=10.7 cm and NI the nearest integer.

The ambiguities solved by equation 3 can be incorporated in the real-time tomographic ionospheric model, improving the ionospheric determination:

$$\alpha\nabla\Delta STEC = \nabla\Delta(L_1 - L_2) - (\lambda_1\nabla\Delta N_1 - \lambda_2\nabla\Delta N_2) \qquad (4)$$

Also, this helps with the real-time geodetic solution – running in parallel with the ionospheric program–, to reduce the number of unknowns and its correlations, to improve the orbit determination and the tropospheric estimation, that is the main subject of this paper[3].

Indeed, once the ambiguities $\nabla\Delta N_1$, $\nabla\Delta N_2$, have been computed as integers, it is possible to compute an unambiguous L_c, that can be used as a very precise absolute ionospheric-free pseudorange. From this kind of datum only, the absolute ZTD can be computed, by means of a geodetic program such as GIPSY (Webb and Zumberge, 1997), emulating the computation in real-time, and only using the forward filter. The tropospheric refraction can be estimated as a random walk process using the Niell mapping functions (Niell, 1996), jointly with the relaxed broadcast orbits and clocks, and the constrained (10 cm) receiver positions.

[3]Notice that in spite of the fixed ambiguities being those of double-differences, they are used to improve undifferenced geodetic and ionospheric solutions.

ALGORITHM: ROVER RECEIVERS

The main difference between the rover and permanent receivers, from the point of view of ambiguity resolution, is the performance of the B_c ambiguity estimation. The quality of the B_c ambiguity will be less due to to the insufficient information in the limited broadcast message and, in many cases, the poorly known a-priori position of the user. But if we are able to provide the user of the rover receiver double differenced ionospheric corrections as accurate as for the reference station solution, after fixing their ambiguities (few cm), we shall be able to overcome this lack of information, and resolve the ambiguities.

In spite of greater errors in B_c –let's say 10-20 cm– it should be possible to fix the widelane ambiguity using the cm-level ionospheric correction, as suggested by equation 1. Having resolved the wide lane, L_1 and L_2 follows, as explained in Colombo et al. 2000.

We can interpolate the precise $\nabla\Delta STEC$, obtained in the reference station solution (by means of equation 4), to the rover receiver position. This interpolation can be done in several ways. If a linear interpolation is used, like in the virtual station approach (for instance Wanninger, 1999), the irregularities of the ionosphere at scales less than the typical distances of the network (few hundred km in our case) will not be taken into account. Then it can be critical to obtaining the required accuracy, as we shall show in the next section.

In this work we propose an algorithm, in which the user computes its own tomographic model of the ionosphere, using only dual frequency GPS carrier phase data from the rover, but constrained by the precise $\nabla\Delta STEC$ broadcasted by the reference network. This can be done in real-time without CPU power problems, for both the ionospheric and positioning software, using for instance a recent standard PC laptop, and running the public domain operative system Linux. The broadcasted $\nabla\Delta STEC$ from the reference stations requires to transmit less than 1024 bytes every 5 minutes for the computations presented in this paper.

Then, once $\nabla\Delta N_\delta$ is fixed, we can obtain the second carrier-phase ambiguity by means of equation 5. Notice that the maximum allowed error in $\nabla\Delta STEC$ to fix correctly $\nabla\Delta N_2$ is $(\lambda_2-\lambda_1)/2$=2.7 cm

$$(\lambda_1-\lambda_2)\nabla\Delta N_2 = \nabla\Delta(L_1-L_2) - \alpha\nabla\Delta STEC - \lambda_1\nabla\Delta N_\delta \qquad (5)$$

Finally, the ZTD can be computed for the rover receiver, using the OTF resolution of the full set of ambiguities, from the precise $\nabla\Delta STEC$ (less than 2.7 cm), as it has been described above. From the derived unambiguous L_c, and the improved orbits transmitted by the reference network to the rover receiver, the troposphere can be computed in real-time mode at the rover, using the same procedure as for the reference stations.

RESULTS IN SCENARIO 1 (IONOSPHERIC DISTURBANCES)

The first data was chosen to test the new strategy for obtaining in real-time the ZTD at a WADGPS-sized network, in the presence of low-moderate geomagnetic activity (Kp in the range 1-4), but containing ionospheric disturbances during the last day. This makes this scenario interesting for seeing just how these conditions affect the key point in the overall strategy: the real-time tomographic modeling of the ionosphere.

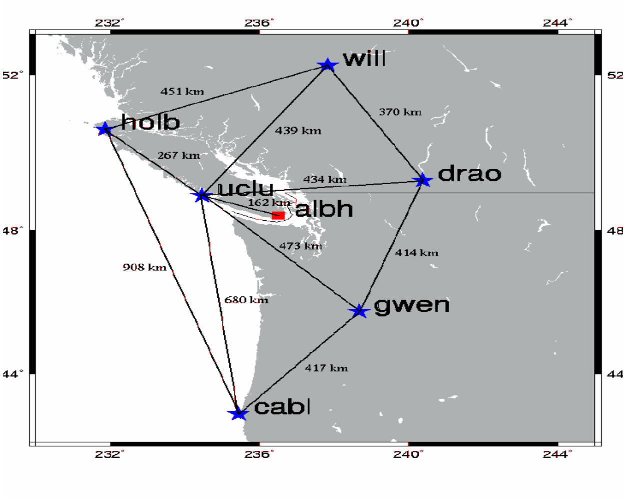

Figure 1: Map of the studied network of GPS stations in North –America.

The data came from a network of 7 GPS receivers in North-America (see figure 1), all participating in the International GPS Service (IGS), for the period of 28-30 April 1998. In this period important small scale ionospheric disturbances were detected during the 3rd day, as shown in figure 5.

Six of the GPS receivers are treated as reference stations (HOLB, WILL, UCLU, DRAO, GWEN and CABL), and ALBH plays the role of rover station, following the strategy described in the previous sections. All of the receivers are Rogue receivers, with the exception of GWEN (Ashtech) and CABL (Trimble). There are IGS tropospheric determinations available for all the stations every two hours, with the exception of CABL and GWEN.

The results obtained in the double differenced widelane ambiguity resolution are given in figure 2 as function of the elevation on the horizon of the GPS satellites. A real-time tomographic model of the ionosphere, using 2 layers of 5x5 deg. voxels in solar longitude and latitude, and updates every 5 minutes with a process noise of 10^{10} e/m^3/$\sqrt{h}$) is used. In the same figure, they can be compared to the results that would be obtained assuming $\nabla\Delta STEC$=0. A success percentage greater than 90% is obtained for elevations as low as 15-20 degrees.

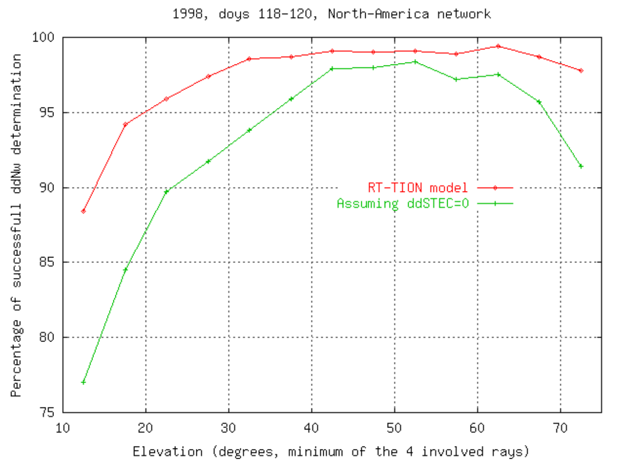

Figure2: Percentage of successful widelane double integer ambiguity determination as a function of the elevation of the lowest satellite, for North-American network (1998, Days 118-120). The results for both tomographic model and neglecting ∇ΔSTEC are indicated.

In figure 3 the tropospheric refraction results for the reference stations using the presented strategy (hereinafter RTROP-OTF) are shown. In these plots the RTROP-OTF strategy is compared with the real-time mode computation floating the ambiguities with all the available data and also relaxing the broadcast ephemerides (RTROP), and with the corresponding post-process solution fixing the ambiguities (TROP). These are the main comparisons to be considered because they do not use data from outside the network. Also the post-processed solutions, or Precise Point Positioning solutions using the orbits and clocks provided by JPL (PPPTROP), and the IGS combined tropospheric solution (IGSTROP), are shown, for reference. The general agreement in ZTD is of the order of 1 cm in absolute, and several mm when the ZTD is taken relative to UCLU (i.e. its difference with the ZTD at that site). This is due to the small size of the network (figure 1) inadecuate for proper broadcast orbits relaxation, causing through correlations with other errors a bias of about 5 mm in the ZTD estimation. Our main

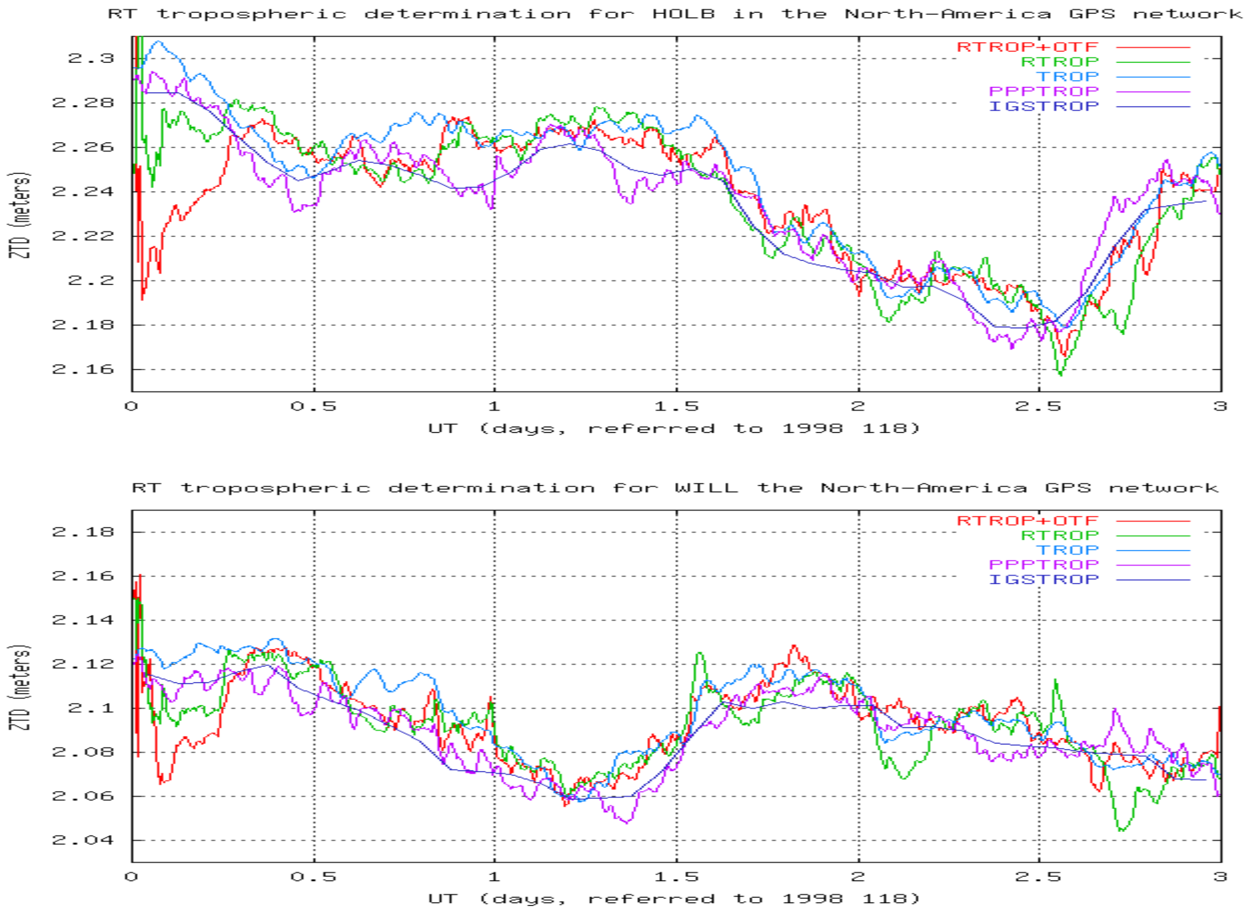

Figure 3: Real-time tropospheric determination using the presented approach (RTROP-OTF), compared with real-time determination also with broadcast orbit relaxation (RTROP), and the corresponding postprocessed determination (TROP), including the IGS one, IGSTROP, and the PPPTROP, all for several reference stations of the Nort-America network.

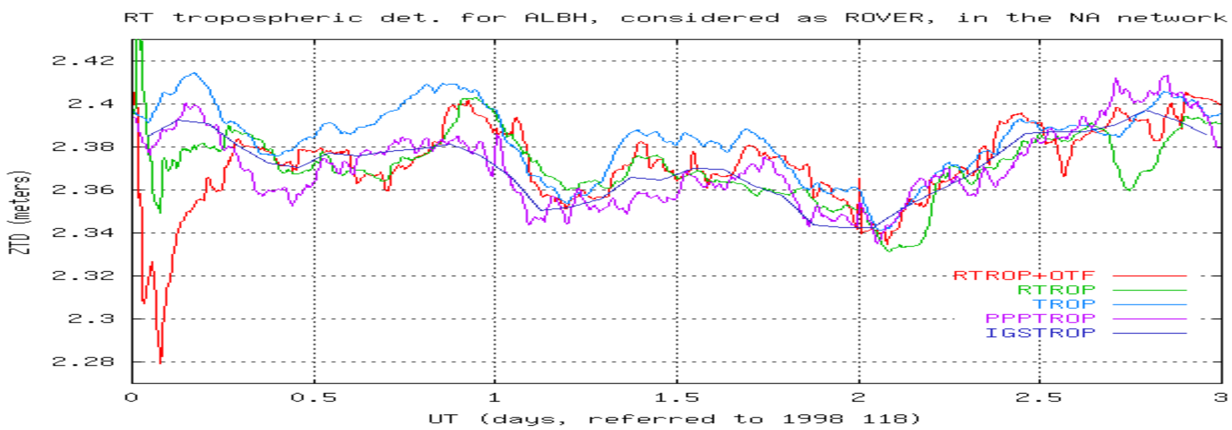

Figure 4: Real-time tropospheric determination of the *rover* receiver ALBH, using the presented approach, compared with real-time determination with orbit relaxation, and postprocessed determinations, including the IGS one (North-America network).

reference here will be the corresponding post-processed tropospheric solution TROP, that deals effectively with the ambiguities, and our main goal is to improve the real-time solution RTROP, that relaxes the broadcast orbits using all the network data, with 40-50% more unknowns than RTROP-OTF due to the floating ambiguity estimation.

Table1: *Bias and RMS (in cm) of the difference between the best postprocessed solution relaxing the broadcast orbits and using only the data of the network (TROP) and (a) our real-time technique relaxing orbits + OTF ambiguity resolution (RTROP+OTF, 2nd and 3rd column), (b) real-time relaxing broadcast orbits (RTROP, 4th and 5th column), and (c) post-processing in PPP mode (PPPTROP, 6th and 7th column). The results for the rover receiver (ALBH) are also shown in the last row.*

	ZTD compared with TROP sol. (cm)					
Rec.	RTROP+OTF		RTROP		PPPTROP	
	Bias	RMS	Bias	RMS	Bias	RMS
Holb	-0.3	0.8	-0.6	1.2	0.6	1.4
Will	0.0	0.6	-0.3	1.0	0.6	1.2
Drao	-0.1	0.8	-0.8	1.3	0.8	1.3
Uclu	-0.4	0.8	-0.8	1.2	1.1	1.6
Cabl	-0.8	1.8	-1.4	2.1	1.6	2.1
ALBH	-0.4	0.9	-1.0	1.3	0.9	1.4
	Same as Above, but ZTD rel. to UCLU (cm)					
Rec.	RTROP+OTF		RTROP		PPPTROP	
	Bias	RMS	Bias	RMS	Bias	RMS
Holb	0.1	0.5	0.2	0.5	-0.4	0.5
Will	0.4	0.8	0.5	1.0	-0.5	0.7
Drao	0.2	0.8	0.1	1.0	-0.2	0.6
Cabl	-0.4	1.5	-0.6	1.3	0.6	1.0
ALBH	-0.0	0.7	-0.1	0.7	-0.2	0.4

A more quantitative comparison can be found in table 1 and 2 where the bias and RMS of each solution at 5 minutes sampling rate are shown regarding to the postprocessing solutions, TROP and PPPTROP respectively, for the absolute ZTD, and for the ZTD relative to UCLU (the IGS solution, every 2 hours, is not included in the tables). In the comparison with the postprocessing solution TROP, that relaxes the broadcast orbits with the same set of stations (see table 1), it can be seen that for the reference stations the faster strategy RTROP-OTF presents an RMS below 1 cm, 40% lower than using RTROP[4], although with the RTROP all of the data are used (20% more than with RTROP+OTF). The improvement is mainly due to the smaller correlations in RTROP+OTF. A 20% improvement is also shown in the tropospheric refractions estimated for WILL and DRAO relative to UCLU.

[4]The exception is the southern station CABL, with an RMS of 1.8 cm, related with its worst ionospheric determination.

The comparison with the precise postprocessed solution (PPP), in which orbits and clocks have been estimated in post-process mode using a worldwide GPS network (instead of the 6-northamerican station network which is only 1000 km in diameter) shows a typical RMS of 1.1-1.4 cm (table 2), a 15%-35% better than with RTROP. A part of this RMS is due to a bias related with the different orbit determination. This can be clearly seen when the ZTD relative to UCLU is considered (second part of the same table 2) for which the RMS is typically only 7-8 mm (again not taking into account CABL), and when the bias and RMS of TROP and RTROP+OTF are compared to those in PPPTROP.

Table2: *Bias and RMS (in cm) of the difference between the post-processing PPP solution (PPPTROP) using worldwide GPS data and (a) our real-time technique relaxing orbits + OTF ambiguity resolution (RTROP+OTF, 2nd and 3rd column), (b) real-time relaxing broadcast orbits (RTROP, 4th and 5th column), and (c) postprocessed solution relaxing the broadcast orbits and using only the data of the network (TROP, 6th and 7th column). The results for the rover receiver (ALBH) are also shown in the last row*

	ZTD compared with PPP sol. (cm)					
Rec.	RTROP+OTF		RTROP		TROP	
	Bias	RMS	Bias	RMS	Bias	RMS
holb	0.3	1.4	0.0	1.8	0.6	1.4
will	0.6	1.1	0.2	1.5	0.6	1.2
drao	0.7	1.3	0.1	1.5	0.8	1.3
uclu	0.7	1.4	0.2	1.6	1.1	1.6
cabl	0.8	1.6	0.2	1.9	1.6	2.1
ALBH	0.5	1.3	-0.1	1.5	0.9	1.4
	Same as Above, but ZTD rel. to UCLU (cm)					
Rec.	RTROP+OTF		RTROP		TROP	
	Bias	RMS	Bias	RMS	Bias	RMS
holb	-0.4	0.7	-0.2	0.6	-0.4	0.5
will	-0.1	0.7	-0.0	0.9	-0.5	0.7
drao	0.0	0.8	-0.2	1.1	-0.2	0.6
cabl	0.1	1.2	-0.1	1.3	0.6	1.0
ALBH	-0.2	0.8	-0.3	0.8	-0.2	0.4

As to the rover station results, those have been obtained as described in the previous section. The key point here is the use of the ambiguity-resolved double-differenced ambiguities to provide a very precise $\Delta STEC$ to the rover station, of better than 2.7 cm, i.e. 0.25 TECU. This is a dificult task, taking into account that during the last of the 3 days the ionosphere presented important disturbances at small scales. The linear interpolation between WILL, GWEN and UCLU fails to provide a precise $\nabla\Delta STEC$ to the rover receiver ALBH (see figure 5), with discrepancies of more than 15 cm. However, when the user of the rover receiver computes his own ionospheric model using only his own dual-frequency carrier phase data, constrained with the very precise $\nabla\Delta STEC$ computed at the reference stations (equation 4), the result improves significantly during the disturbances.

The overall success in the $\nabla\Delta STEC$ interpolation to the user location, with the help of the constrained real-time ionospheric model, can be seen in figure 6. Practically all the time, the success rate is over 80%, with the exception of two small periods at 1.65 and 2.2 days which are related to a bad election of reference satellite and to the mentioned disturbance period of the ionosphere, respectively.

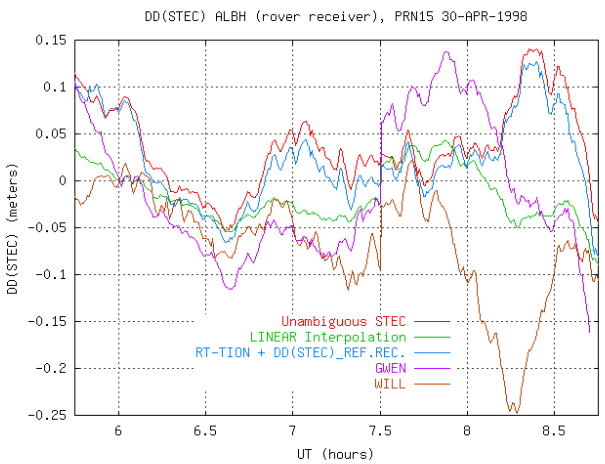

Figure 5: Example of the improvement in the $\Delta\nabla$ STEC interpolation for the rover receiver, when a real-time tomographic ionospheric model –constrained with the $\Delta\nabla$ STEC in the reference receivers– is used instead of a linear interpolation model (using the reference stations UCLU, WILL and GWEN in the North-America network). In this dataset the ionosphere presents small scale ionospheric disturbances.

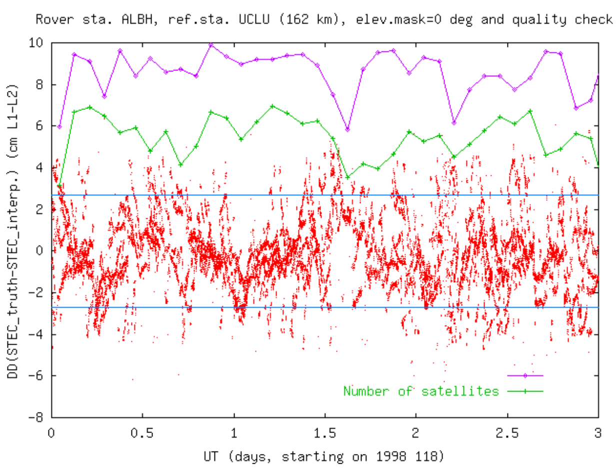

Figure 6: Success in the $\Delta\nabla$ STEC interpolation to the rover receiver ALBH (points within the limits +/-2.7 cm).

The results for tropospheric refraction at the rover receiver are shown in figure 4 and in tables 1 and 2. A good agreement is generally obtained[5] with the postprocessed solution TROP, of the order of 0.9 cm RMS for the absolute ZTD, and improving a 30% on the result using float ambiguities (RTROP).

RESULTS IN SCENARIO 2 (SOLAR MAXIMUM PEAK)

The OTF ambiguity resolution based on the real-time ionospheric modelling suffers from the strong spatial and temporal gradients in the ionosphere. In order to continue exploring the performance of the proposed method, we present the first results during the recent Solar Maximum peak (see figure 8), with several European stations (figure 7) during four consecutive days, 110-113 of 2000. In this second scenario the geomagnetic activity is low to moderate (Kp below 4), but the typical vertical Total Electron Content value at noon is 60 TECU (and STEC until 300 TECU and more), i.e. 3 times the values in 1998.5 as it can be seen in figure 8.

The main network, i.e. the stations used to solve OTF the ambiguities and to get the real-time ZTD, are formed by the IGS permanent receivers BRUS, POTS, OBER and HELG (see figure 7), and WSRT that will be treated as rover receiver. An additional ring of IGS receivers, HERS, ONSA, LAMA, PENC and UNPG, and the permanent Ashtech Z-XII receiver at GAGE, in our university, have been used only to compute the ionospheric model. The selection of this data set (figure 8) has been constrained to meet several additional criteria, among those mentioned for Solar Maximum peak: (1) avoiding as many Rogue receivers, and using as many Ashtech receivers as possible (worst and best performance, respectively, in scenarios with severe variations of ionospheric refraction, Skone et al. 1999), (2) To have distances of WADGPS networks (more than 300 km between the reference stations). To have significant water vapor content variations, i.e. both interesting tropospheric and ionospheric weather, has been an additional goal in our selection.

Once the ionospheric tomographic model is updated in real-time mode, the double differences of the widelane ambiguities are computed. The corresponding percentage of success for the reference stations can be seen in figure 9 as a function of the elevation above the horizon of the lowest GPS satellite used to form a double difference. It can be seen that in this case with extremely high STEC values, it is specially important to incorporate

[5] This happens after an initialization period of several hours during the first day, needed to decorrelate the troposphere from the other estimated parameters, like the satellite orbits. Notice that this is not a problem for a continuously working reference station network.

in the real-time tomographic ionospheric model the resolved ambiguities as constrains in $\nabla\Delta STEC$: in this way a success rate of more than 80% at elevations lower than 20 degrees and 90% at 25 degrees are obtained. However, if the fixed ambiguities are not incorporated in the ionospheric model, the success diminishes to about 10% below 50 degrees of elevation. This matters most in the afternoon, when the highest STEC values happen.

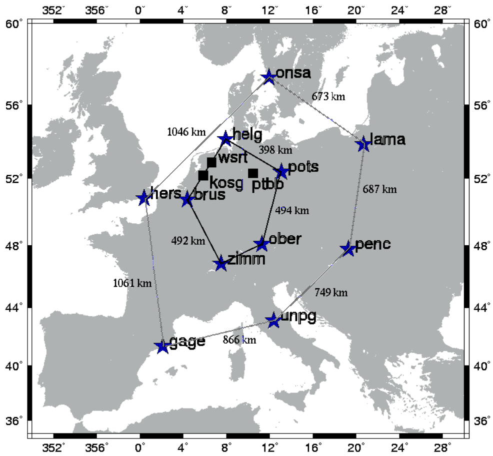

Figure 7: Map of the studied network of GPS stations in Europe.

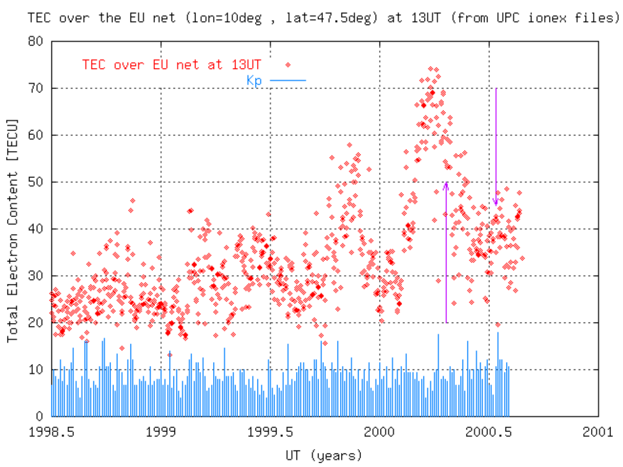

Figure 8: Total Electron Content over Europe (longitude=10 deg., latitude=47.5 deg.), obtained from the UPC ionex files –computed in the framework of the IGS ionospheric project–. The beginning of the data analyzed in scenario 2 and scenario 3 are indicated with vertical arrows (days 110 and 194 of year 2000). The Kp index is also represented.

After fixing, in real-time mode, the full set of ambiguities, the tropospheric refraction obtained agrees with the postprocessed solutions to about 1 cm (or better, in some periods), and with maximum deviations of less than 3 cm (see figure 10). These results are obtained in the context of extreme ionospheric conditions that reduce the number of ambiguities resolved, especially in the afternoon, reducing the amount of useful data to compute the real-time troposphere.

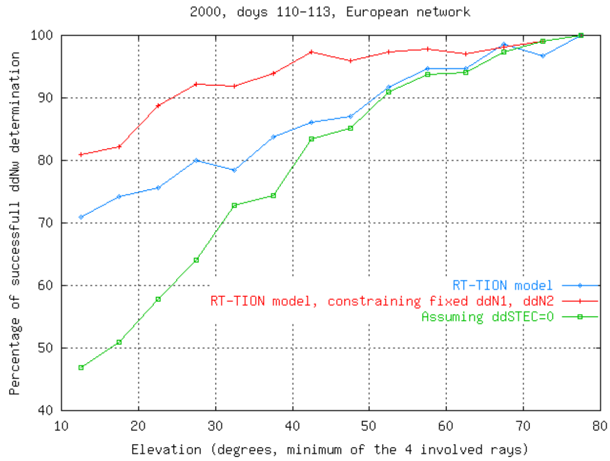

Figure 9: Percentage of successful widelane double integer ambiguity determination as a function of the elevation –of the lowest satellite of the involved rays in each double difference–, for the European network, and in the Solar Cycle maximum peak (222, days 110-113).

In the resolution of the rover receiver ambiguities, the success rate for both ambiguities $\nabla\Delta N_1$, $\nabla\Delta N_2$, after fixing OTF its own resolved ambiguities is typically about 75%, and between 100% and 50% in the afternoon, due to the extreme ionospheric conditions (the success diminish a 25% if the ambiguities of the rover are not asimilated OTF). This affects the resolution of the ZTD in the rover with strategy RTROP+OTF resulting in an RMS with the corresponding postprocess solution TROP of 1.3 cm (see more details in figure 11). The corresponding solution in real-time floating the ambiguities (RTROP) provides very bad results (RMS of 3.6 cm). The comparison with PPPTROP provides an RMS of 1.5 cm, in front of 4.2 cm with RTROP.

ESTIMATING WITH HIGH GEOMAGNETIC ACTIVITY AT SOLAR MAXIMUM

With the same European network, but whithout ZIMM (see figure 7), we have also tested the performance of one of the strategy fundamentals (on the fly resolution of the carrier phase ambiguities) in the context of 3 consecutive large geomagnetic storms. The index Kp reached peaks between 7 and 9 (i.e. strong to extreme geomagnetic conditions following Poppe, 2000) during 4 consecutive days, in the Solar maximum part of the cycle (year 2000, days 194-197).

The results of the widelane ambiguity resolution for the reference network can be seen in figure 12, as a function on time, shown at 3 hour intervals in order to be

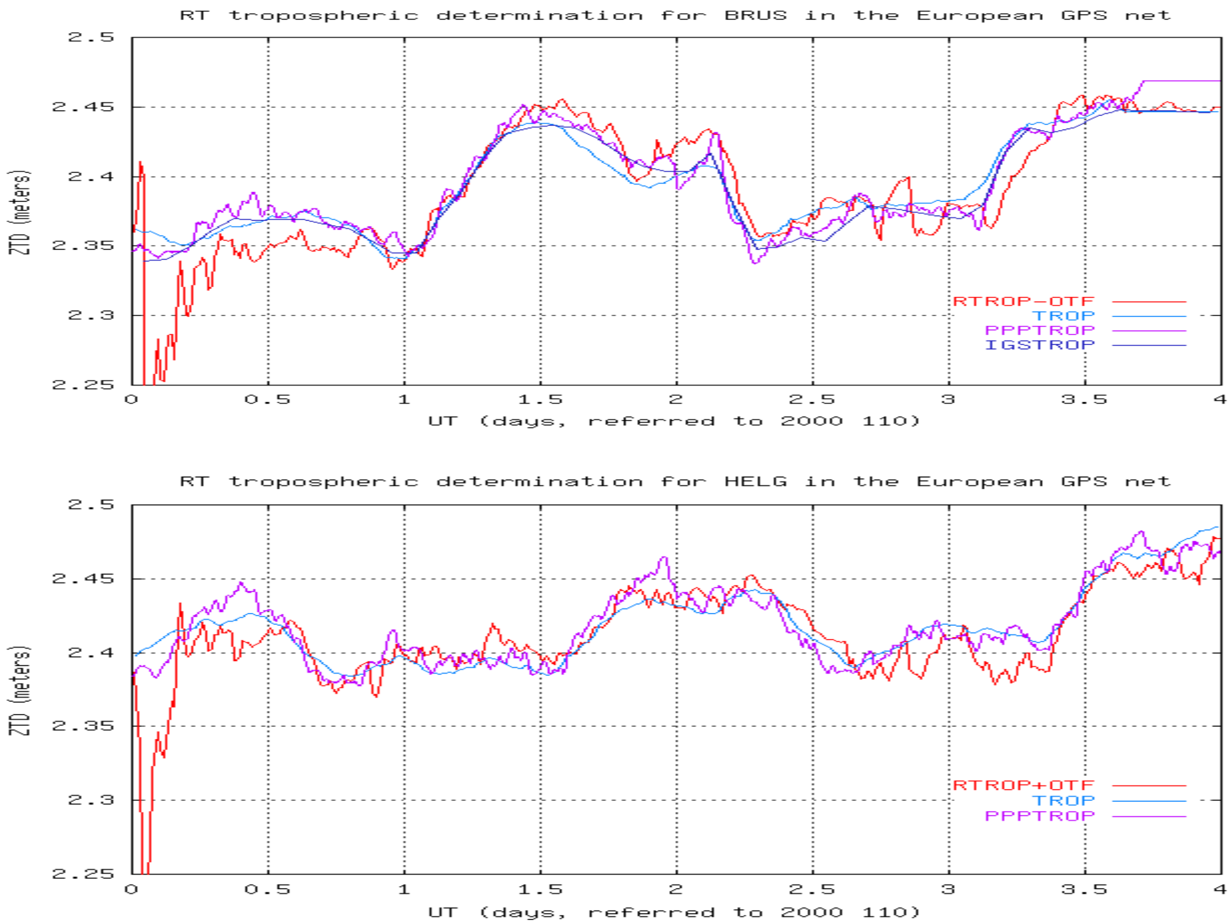

Figure 10: Real-time tropospheric determination using the presented approach (RTROP-OTF), compared with real-time determination also with broadcast orbit relaxation (RTROP), and the corresponding postprocessed determination (TROP), including the IGS one, IGSTROP, and the PPPTROP, all for several reference stations of the European network, in the Solar Maximum peak, days 2000 110-113 (scenario 2).

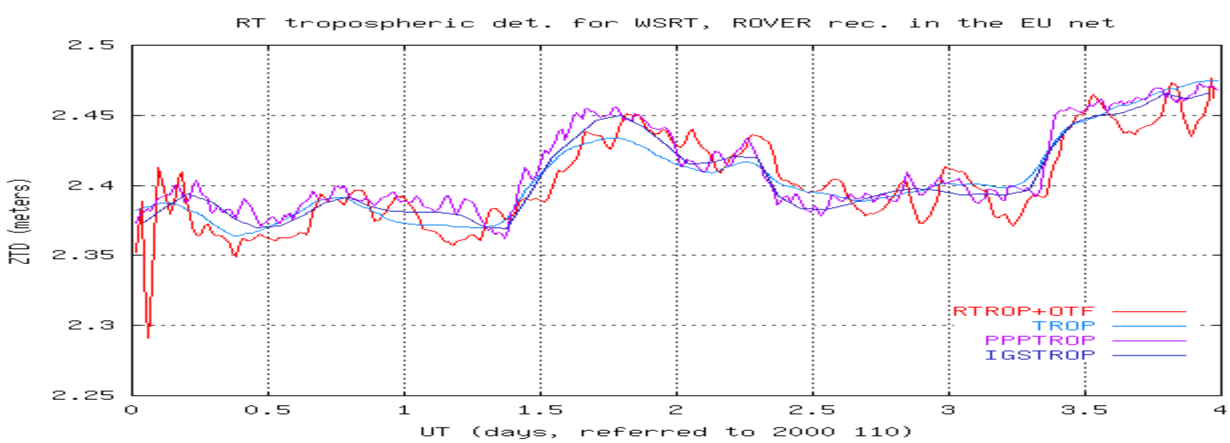

Figure 11: Real-time tropospheric determination of the *rover* receiver WRST, using the presented approach, compared with real-time determination with orbit relaxation, and postprocessed determinations, including the IGS one, also for Scenario 2.

directly compared with the Kp index evolution. The need of using the tomographic model is evident, with typical success rate of 90% during the first –geomagnetically quiet– day, compared to the 50% success when $\Delta STEC$ is neglected. Coinciding with the first Kp index increase, until 7 in the noon of the second day, the percentage when using the ionospheric correction falls to typically 75-80%. During the third day the Kp continues increasing, with a new peak of Kp=7.3 in the afternoon, when the percentage falls to 60%. In the extreme conditions at the end of the 4th day, when Kp reachs its maximum value of 9, the percentage drops to 50%. The interpolation of the double-differenced ionospheric correction to the rover receiver WSRT, works well during the first, quiet day, with percentages of full ambiguity resolution about 60-70%. This success drops to 20-40% coinciding with the 3 geomagnetic storms. The research about this and other new relevant data sets continues in the moment of writing this paper.

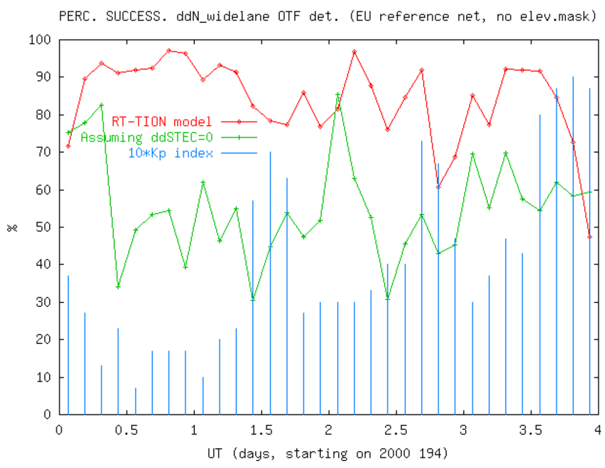

Figure 12: Percentage of successful widelane double integer ambiguity determination as a function of time, for the European network, during several consecutive large geomagnetic storms in the Solar Cycle max. (2000, 110-113). The results neglecting $\Delta\nabla\, STEC$ are also plotted.

CONCLUSIONS

With the help of a real-time tomographic ionospheric model, ambiguities can be solved on the fly (OTF) in WADGPS networks for both reference and rover receivers. This can be used to compute in real-time, instantaneously, the ZTD with an accuracy of 1 cm RMS, which can be used for the determination of integrated water vapor.

It is shown that this approach can also work under adverse scenarios for ionospheric modeling, one key point in favour of this strategy. Scenarios were tested with ionospheric disturbances at small distance scales, Solar Maximum peak and large geomagnetic storms in Solar Maximum conditions.

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REFERENCES

Bevis M., S. Businger, T.A. Herring, C. Rocken, R.A. Anthes, and R.H. Ware, GPS Meteorology: Remote Sensing of Atmospheric Water Vapor for Meteorology, J. Geophysical Res. 97, pp. 15787-15801, 1992.

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

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.

Colombo O.L., Hernandez-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.

Coster A.J., A.E. Niell, H.K. Burke and M.G. Czerwinski, The Westford Water-Vapor Experiment: Use of GPS to Determine Total Precipitable Water Vapor, Lincoln Laboratory M.I.T. Technical Report 1038, 1997.

Ge, M., E. Calais and J. Haase, Reducing satellite orbit effects in near real-time GPS zenith tropospheric delay estimation for meteorology, Geophysical Research Letters, 27, 1915-1918, 2000.

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 Res. Letters, 27, 2009-2012, 2000.

Niell, A.E., Global mapping functions for the atmosphere delay at radio wavelengths, Journal of Geophysical Research, 101, 3227-3246, 1996.

Poppe, B.B., New Scales Help Public, Technicians Understand Space Weather, EOS transactions AGU, 81, p. 328, 2000.

Skone, S., M.E. Cannon and M. Dejong, The impact of geomagnetic substorms on GPS receiver performance, and correlation with space weather indices, GPS 99 in Tsukuba, Japan, October 1999.

Van der Hoeven, A.G.A., B.A.C. Ambrosius, H. van der Marel, H. Derks, H. Klein Baltink, A. van Lammeren, and A.J.M. Kösters, Analysis and Comparison of Integrated Water Vapor Estimation from GPS, ION GPS'98, Nashville, USA, September 1998.

Wanninger L., The Performance of Virtual Reference Stations in Active Geodetic GPS-networks under Solar Maximum Conditions, ION GPS'99, Nashville, USA, Sept. 1999.

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