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A new strategy for real-time integrated water vapor determination in WADGPS networks

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Abstract. A major issue in many applications of GPS is the real-time estimation of the Zenith Tropospheric Delays (ZTD). Several authors have developed strategies that estimate ZTD, with a latency of one hour or more in order to compute Integrated Water Vapor (IWV), using local measurements of surface pressure, or to assimilate ZTD into Numerical Weather Predicition (NWP) models. These strategies require that data from a regional GPS network be processed in near real-time, using precise IGS orbits and partial orbit relaxation. Recently it has been shown that in Wide Area Differential GPS (WADGPS) networks of several hundred kilometers 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 show how ambiguity resolution can help determine in real-time the ZTD for a WADGPS network user, only 10-20% worse than those of the post-processed solutions.

1. Introduction

As widely demonstrated in recent years, the Global Positioning System (GPS) can provide reliable estimates of the Zenith Tropospheric Delay (ZTD), with high availability and temporal resolution which can be used to derive the Integrated atmospheric Water Vapor (see for example *Bevis et al.,* 1992, *Coster et al.* 1997, *van der Hoeven et al.,* 1998).

The closer to being obtained in real time, the greater the relevancy of GPS-derived ZTD to weather forecasting. If possible, latency should not exceed 1 hour 45 minutes, as it has been recommended by working group 3 of the COST-716 action (http://www.oso.chalmers.se/ ~kge/cost/ Oslo_WGmeetings.pdf). Until now, one of the main difficulties in getting true real-time ZTD has been the lack of a dependable availability of precisely predicted orbits (*Ge et al.,* 2000). This makes it necessary to correct those orbits that are available, even when they are not very precise (e.g., the broadcast ephemerides), estimating satellite orbit error states jointly with the ZTD, within a data window long enough (usually up to 24 hours) to ensure a reliable final estimate. But this computational strategy usually creates latencies of about one hour or more.

In this paper we show that, even when using broadcast orbits (instead of using precise real-time orbits like in *Muellerschoen et al.* (2000)), it is possible to estimate in real time the ZTD with a precision of 1 cm (1 mm precipitable IWV $\simeq$ 6.7 mm ZTD approximately). This can be done instantaneously, based on the rapid resolution of the ambiguities of double-differenced carrier phase data, using networks consisting of reference GPS stations separated by hundreds of kilometers, like the WADGPS networks. This rapid ambiguity resolution, on-the-fly (OTF) ambiguity resolution techniques with precise ionospheric corrections, can be achieved through the integration of a real-time tomographic model of the ionosphere with a real-time positioning strategy (*Colombo et al.* 2000, 1999 and *Hernández-Pajares et al.,* 2000). Fixing ambiguities OTF helps tropospheric determination, because the carrier-phase observations can be treated as very precise ranges, not just in double-differenced processing, but also in undifferenced, or absolute processing. This strategy diminishes the number of unknowns to be solved by about 50% and, hence, the computational load, and it also tends to decorrelate the troposphere from the other estimated parameters. All this is especially important when using a Kalman filter in real-time WADGPS navigation, often without the benefit of long data windows (several hours), as in post-processing.

This approach allows also any user not belonging to the reference network (hereinafter rover) to estimate in a precise way the ZTD (1.4 cm r.m.s. in this study), without increasing the network computational load. This opens the new possibility of easily deploying, in regions with WADGPS networks (like U.S.A. or Europe) many GPS receivers working as real-time meteorological sensors. In the next section we will summarize the algorithm, and present the results of a test lasting several consecutive days, in Solar Maximum conditions.

2. Technique

We have followed the procedure described in (*Colombo et al.,* 2000) and in the flow chart of *Hernández-Pajares et al.,* 2000 (figure 1) for long-baseline OTF ambiguity resolution, which consists on different algorithms for the reference and rover receivers. Two modifications have been been included. The first one is to use the double-differenced carrier-

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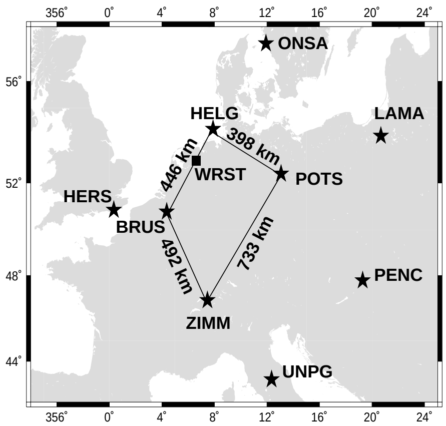

Figure 1. Map of the GPS stations used in this paper.

phase ambiguities after they have been resolved within the reference network, to improve the ionospheric model. The second one is that at the rover the interpolated ionospheric corrections from the reference network are refined using the undifferenced data from the rover. These changes, as shall be seen in the Results section, improve the ambiguity resolution for the rover. In turn, the resolved ambiguities help to determine the tropospheric ZTD at the rover with greater accuracy. The computing needs of the user can be met with an ordinary PC, and the data broadcasted from the reference stations, during the test described in this paper, would have required transmitting less than 1024 bytes every epoch.

2.1. Reference stations network

The first objective is to fix the double-differenced ambiguity $\nabla\Delta N_\delta$ of the widelane combination L_δ of the L_1 and L_2 carrier phases to an integer value. One can exploit the fact that the coordinates of the reference stations are already known at the centimeter level. This allows the estimation, with a precision of a few centimeters, of the overall effect of orbit errors, the reference stations tropospheric refractions ZTD's, and the L_c ionospheric-free carrier-phase combination biases B_c. The standard technique to determine these unknowns involves post-processing the data using a geodetic program. We have emulated the computation in real-time, using only the forward filter. Now, by subtracting $\nabla\Delta(L_c - B_c)$ from the double differenced widelane combination $\nabla\Delta L_\delta$, orbit and troposphere errors are removed from the widelane. However, the double-differenced widelane is still affected by ionospheric refraction at the level of several decimeters. This has to be corrected to better than 0.25 cycle (standard deviation) in order to be able to fix $\nabla\Delta N_\delta$ (see 1). As explained in (*Hernández-Pajares et al.,* 2000), the double-differenced Slant Total Electron Content ($\nabla\Delta STEC$) can be computed in real time with a standard deviation of 20 cm in widelane combination ($\simeq$1 TECU=10^{16} electrons/m^2), using a tomographic model based on the network GPS carrier-phase data. Once $\nabla\Delta N_\delta$ is fixed, rounded to the closest integer from

$$\lambda_\delta \nabla\Delta N_\delta = \nabla\Delta L_\delta - \alpha_\delta \nabla\Delta STEC - \nabla\Delta L_c + \nabla\Delta B_c \quad (1)$$

($\alpha_\delta \simeq$20 cm/TECU, $\lambda_\delta \simeq 86\ cm$), we can use it and the approximate estimate of $\nabla\Delta B_c$ to solve, fix and validate the full set of double-differenced ambiguities $\nabla\Delta N_1$ and $\nabla\Delta N_2$ (in cycles) of L_1 and L_2 (in length units). With the double differenced ambiguities $\nabla\Delta N_1$, $\nabla\Delta N_2$, the exact value of B_c can be computed to get the unambiguous L_c, which becomes then effectively a very precise, ionospheric-free, and unbiased range measurement. The fixed ambiguities are also used to improve the ionospheric model. With only that precise range as data, the ZTD at the reference stations can be estimated again, this time at the cm-level, as a random walk process, using the Niell mapping functions (*Niell,* 1996), jointly with the relaxed broadcast orbits and clocks, and constrained (1-10 cm) receiver positions. This also produces locally improved orbits that can be broadcasted from the network for the benefit of the users.

2.2. Rover receivers

The main difference between the rover and permanent receivers, from the point of view of ambiguity resolution, is that the position of the receiver is less well known. So this position has to be estimated, along with the other unknowns present in the case of the reference stations. Over baselines hundreds of kilometers long this can be done at the 10-20 cm- level (less than $0.25\lambda_\delta$) after collecting a few minutes' worth of data (*Colombo et al.,* 2000). At that point, by providing the user accurate ionospheric corrections for the double differences with respect to one or more reference stations, the rover ambiguities can be fixed.

One can interpolate the precise $\nabla\Delta STEC$, obtained in the reference station solution, to the rover receiver location, in one of several ways. If a linear interpolation is used, as in the virtual station approach (for instance *Wanninger,* 1999), the irregularities of the ionosphere at scales less than the typical distances for a WADGPS network (several hundred km in our case) cannot be taken into account. This can seriously reduce the accuracy of the interpolated ionospheric correction, and cause an incorrect ambiguity resolution that can corrupt the end result (the rover ZTD), as can be seen in *Hernández-Pajares et al.,* 2000b (figure 5). To overcome this problem, in this work we propose a procedure whereby the user also computes a tomographic model of the ionosphere, using only dual-frequency GPS carrier phase data from the rover, but constrained by the precise $\nabla\Delta STEC$ data broadcasted by the reference network. Next, one resolves on-the-

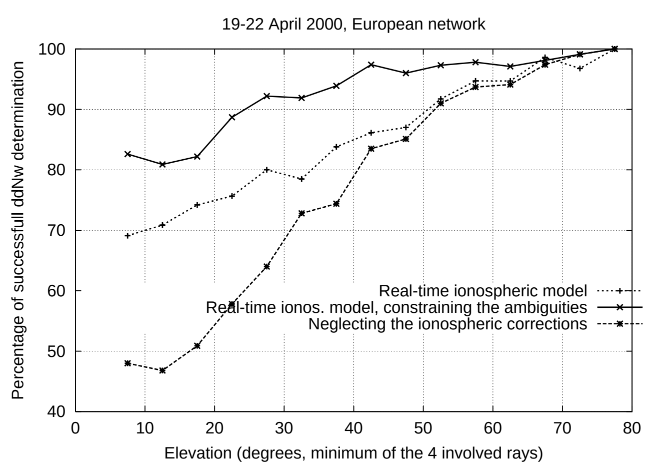

Figure 2. Percentage of successfully fixed widelane double integer ambiguity, as a function of the elevation –of the lowest satellite in each double difference–.

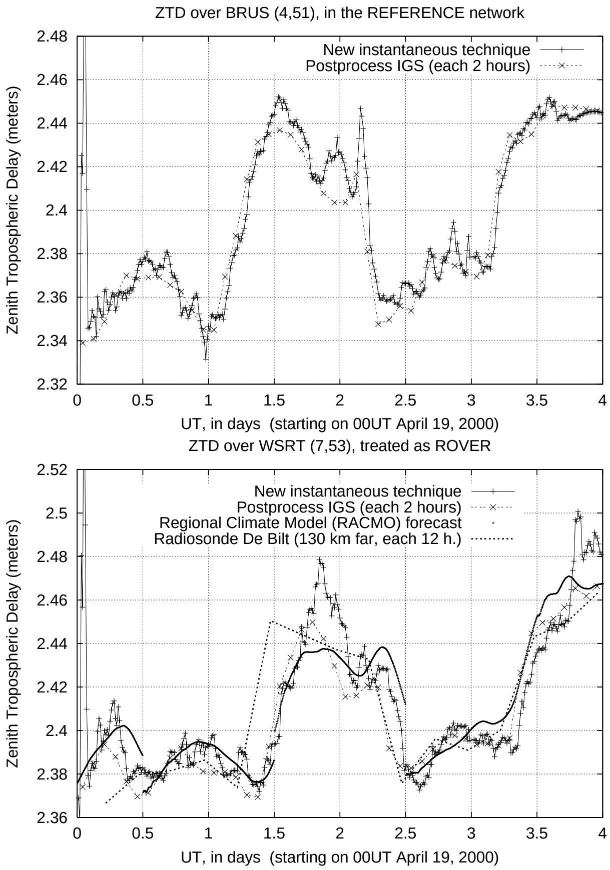

Figure 3. ZTD estimates for the reference network station BRUS (Brussels), made using the new real-time technique and the post-processed solution distributed by the IGS. In the second plot, the new technique solution is also compared with the Regional Climate Model (RACMO) predictions for WSRT (treated as rover) and with the De Bilt radiosonde determination at 130 km distance (the forecast is started at noon every day).

fly the ambiguities for the double-differences between rover and reference stations, from the precise $\nabla\Delta STEC$ (better than 2.7 cm), as it has been mentioned in the previous section, using also equation 1 to get the widelane ambiguity (but with a more precise ionospheric correction and a less precise $\nabla\Delta B_c$). Another independent relationship must be used, in our case exploiting the precise $\nabla\Delta STEC$, to estimate and fix a second ambiguity:

$$(\lambda_1 - \lambda_2)\nabla\Delta N_1 = \nabla\Delta(L_1 - L_2) - \alpha\nabla\Delta STEC - \lambda_2\nabla\Delta N_\delta \quad (2)$$

being $\alpha \simeq 10$ cm/TECU (see *Hernández-Pajares et al.,* 2000, and the corresponding flow chart for more details). Using the resulting unambiguous L_c as data, and the improved orbits transmitted by the reference network to the rover receiver, the troposphere ZTD at the rover can be computed in real-time, using the same procedure as for the reference stations.

3. Results and conclusions

The OTF ambiguity resolution based on real-time ionospheric modeling can be adversely affected by radio propagation problems due to strong spatial and temporal gradients in the ionosphere. This occurs frequently during periods of high solar activity. In order to demonstrate the performance of the proposed method, we present results based on GPS data collected during the recent Solar Maximum peak, at several European stations, (figure 1) during four consecutive days, 19-22 April 2000. In this period the geomagnetic activity is low to moderate (Kp below 4), but the typical vertical Total Electron Content (TEC) value at noon is 60 TECU (and the STEC can reach 300 TECU and more).

The main network of stations used to solve OTF the ambiguities and to get the real-time ZTD, is formed by the IGS permanent receivers BRUS, POTS, HELG and ZIMM (see figure 1). The IGS station WSRT will be treated as the rover receiver. An additional ring of IGS receivers, HERS, ONSA, LAMA, PENC and UNPG has been used mainly to compute the ionospheric model and to support the orbit relaxation. The selection of these stations has been affected by several criteria: first, IGS sites with new receivers were preferred to those with old receivers (considering how they respond to severe variations in ionospheric refraction); secondly, stations separated by distances typical of WADGPS networks were selected (more than 300 km between the reference stations). Also, to have significant water vapor content variations, in the context of high TEC values and gradients, has been an additional goal in our selection: During the selected days three consecutive weather fronts crossed, from West to East, the region (see for instance corresponding METEOSAT images at http://www.satmos.meteo.fr/), affecting with different intensity and at different epochs the network stations.

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 2 as a function of the elevation above the horizon of the lowest GPS satellite used to form any double difference. It can be seen that it is important to incorporate in the real-time tomographic ionospheric model the resolved ambiguities as constraints when estimating the precise $\nabla\Delta STEC$. This results in a success rate of more than 80% at elevations lower than 20 degrees and 90% at 25 degrees. However, if the fixed ambiguities are not used to constrain the ionospheric model, the success rate is about 10% lower below 50 degrees of elevation.

After fixing in real-time the full set of ambiguities, the tropospheric refraction is estimated as a random walk, with a process noise of 5 mm/$\sqrt{\text{hour}}$). The elevation mask is 8 degrees, the nominal hydrostatic component is modeled by an exponential law in term of the ellipsoidal height, and the Niell mapping functions are used as has been mentioned previously.

In order to determine the accuracy of the real-time ZTD, we can compare it with a postprocessed reliable estimation, like the IGS ZTD solution (table 1 and figure 3), determined every 2 hours from several centers (taken as the reference solution in the table). The ZTD estimation obtained for the reference stations agrees with the IGS post-processed solutions to about 1 cm or better, only slightly worse than the agreement between different postprocessed solutions. In particular, we also compared the real-time ZTD with a post-processed solution from Van der Hoeven et al. (1998), with ZTD's estimated every 6 minutes, which confirmed the previous findings. An external comparison with a regional climatic model (RACMO) and a radiosonde determination (130 km far away from WSRT) are also included in the same figure, showing a reasonable agreement.

Table 1. Bias and RMS (in cm) of the difference between the IGS postprocessed solution, for: (a) the proposed real-time technique relaxing orbits + OTF ambiguity resolution (2nd and 3rd column), (b) post-processing mode using the same network data (4th and 5th column). The results for the rover receiver (WSRT) are also shown in the last row.

	ZTD compared with IGS TROP sol. (cm)			
Rec.	Instant.		Post.	
	Bias	RMS	Bias	RMS
brus	0.4	**1.0**	0.5	**0.9**
pots	0.5	**0.9**	0.3	**0.6**
zimm	0.4	**1.0**	0.3	**0.7**
onsa	0.0	**0.8**	0.0	**0.7**
wsrt	0.5	**1.4**	0.4	**0.7**

These results are obtained in the context of the above mentioned Solar Maximum ionospheric conditions, that reduce the number of ambiguities properly resolved, and also decrease the amount of useful data available to compute troposphere in real time.

In the resolution of the rover receiver ambiguities, the mean success rate for both $\nabla\Delta N_1$ and $\nabla\Delta N_2$ is about 80%. This affects the estimates of the ZTD at the rover made with the new strategy, so now the differences with the IGS post-processed results have an r.m.s value of 1.4 cm (see more details in figure 3, third plot). However, not fixing the ambiguities at all produces definitely worse results (r.m.s. of 3.6cm).

From all this, we conclude that the ZTD can be computed in real-time, very rapidly[1], with an accuracy of about 1 cm RMS in WADGPS networks for both reference and rover receivers (0.8-1.0 cm and 1.4 cm respectively, table 1), i.e. only 10-20% worse than the post-processed techniques. This is achieved with the help of a real-time tomographic ionospheric model to solve the carrier phase ambiguities over long baselines.

This approach works under Solar Maximum conditions, in adverse scenarios for ionospheric modeling, a key point when choosing a robust GPS strategy. Other difficult scenarios, including strong ionospheric disturbances at small distance scales, have been successfully tested elsewhere (*Hernández-Pajares et al.* 2000b.)

These results suggest that real-time ambiguity resolution not only can enhance the present applications of wide-area GPS networks, for navigation and surveying, but may also lead to new applications in the field of meteorology.

Finally, it can be noticed that this real-time ZTD estimation technique could be improved with other techniques focused on the real-time orbit determination, and also with the upcoming GPS modernization and Galileo systems with 3 available frequencies. Furthermore it seems that in these new systems the ionosphere will still limit the distance in which the real-time ambiguity resolution is feasible (*Jung et al. 2000*). In this regard we think that the real-time tomographic modelling of the ionosphere can also be useful.

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[1]The ZTD is estimated at every real-time update of the user's Kalman filter. In this example, every five minutes.

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