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Application of tomographic ionospheric corrections in WADGPS networks for real-time estimation of integrated water vapour

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 ionospheric 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

In recent years several authors have developed strategies that estimate the Integrated Water Vapor (IWV), proportional to the Zenith Tropospheric Delay (ZTD), in near real time --i.e. with a delay of one hour or more--. The success of these estimations depends on the accuracy of the GPS orbits, so these strategies require that data from a regional GPS network be processed in near real-time, using predicted IGS orbits in combination with partial orbit relaxation.

Ambiguity resolution can help determine in real-time such quantities as the ZTD in a regional network. This approach allows any user in the area of the network to get real-time precise ZTD estimates, which can be converted to IWV using measurements of atmospheric pressure. As shown recently, 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.

The comparison between the real-time strategy presented in this work and the postprocessed approach shows a general agreement of about 1 cm in the ZTD in WADGPS scenarios. This is 30-40% better than without fixing the carrier phase ambiguities. These results can be

achieved not only in quiet ionospheric conditions, but also during ionospheric disturbances and Solar Maximum conditions. This is also of importance for ionospheric modeling, which is a key element of the technique.

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.

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 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,

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

$$L_I = L_1 - L_2 = \underbrace{\sum_i \sum_j \sum_k (N_e)_{i,j,k} \Delta s_{i,j,k} + b}_{\alpha\ STEC} \qquad (2)$$

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[2].

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.

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 $\alpha\nabla\Delta STEC$ 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.

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

RESULTS

The data chosen to test the new strategy for obtaining in real-time the ZTD at a WADGPS-sized network, were measured 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.

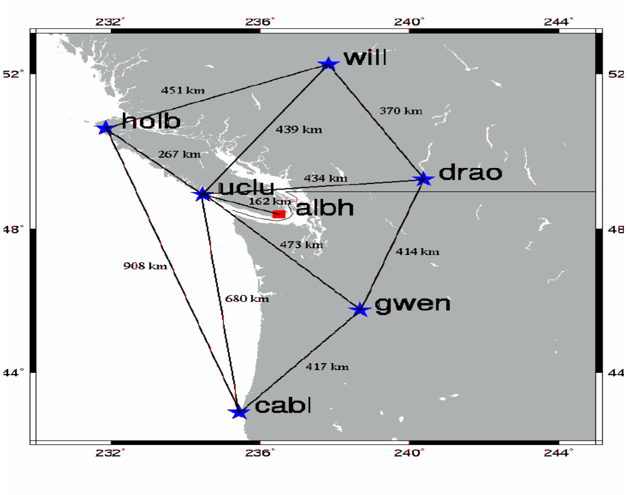

Figure 1: Map of the studied network of GPS stations in North –America.

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.

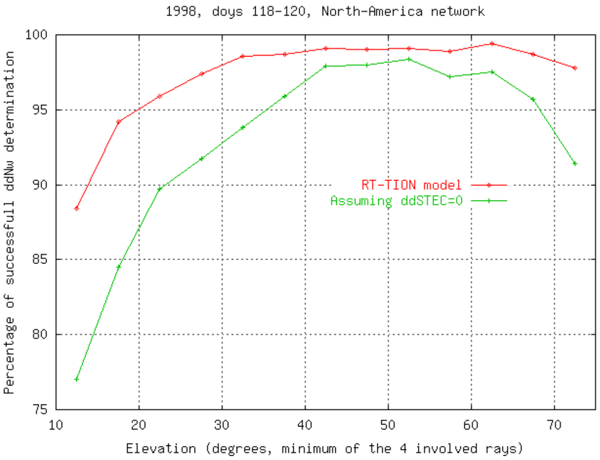

Figure2: Percentage of successful widelane double integer ambiguity determination as a function of the elevation of the lowest satellite, for North-American network (1998, Days 118-120). The results for both tomographic model and neglecting ∇ΔSTEC are indicated.

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 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.

A more quantitative comparison can be found in table 1 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

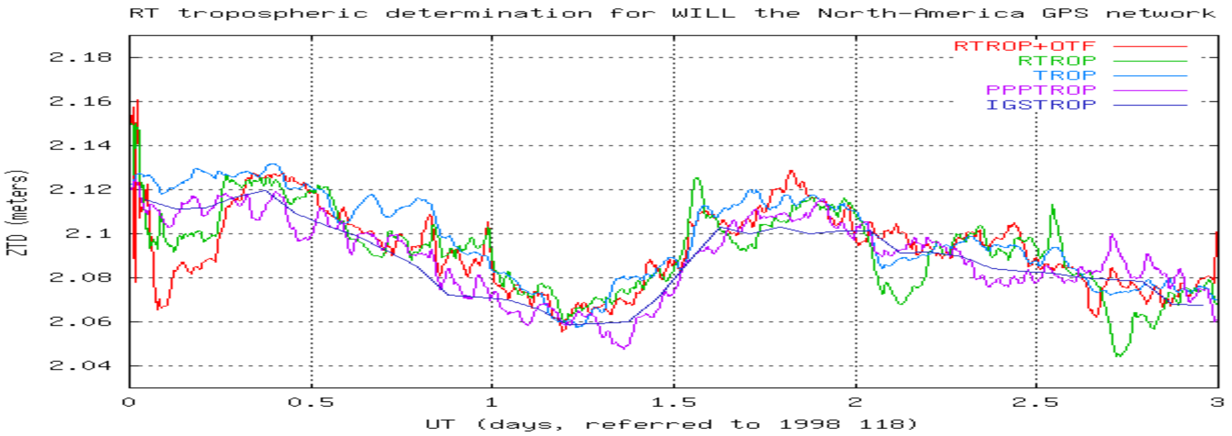

Figure 3: Example of real-time tropospheric determination using the presented approach (RTROP-OTF), compared with real-time determination also with broadcast orbit relaxation (RTROP), and the corresponding postprocessed determination (TROP), including the IGS one, IGSTROP, and the PPPTROP (station WILL).

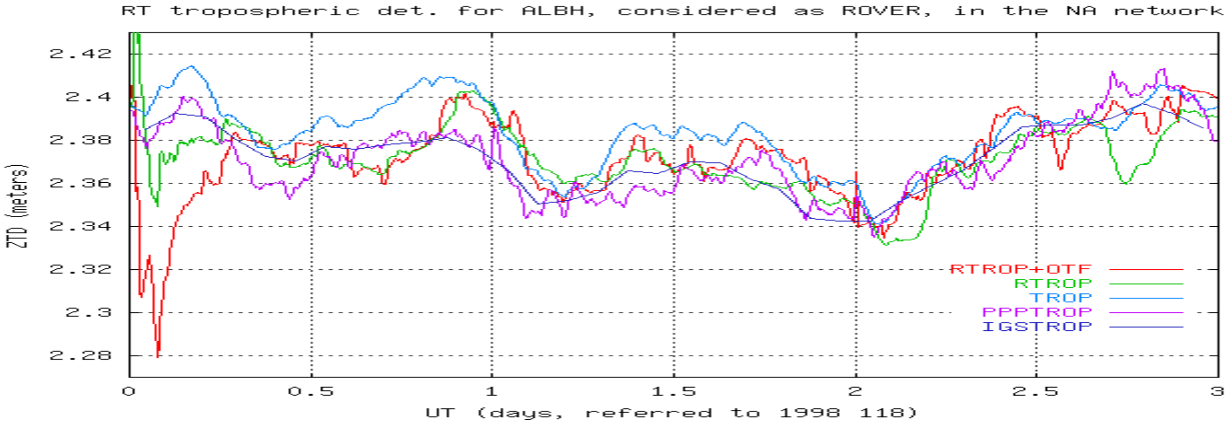

Figure 4: Real-time tropospheric determination of the *rover* receiver ALBH, using the presented approach, compared with real-time determination with orbit relaxation, and postprocessed determinations, including the IGS one (North-America network).

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 rec. (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

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[3], 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.

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.

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

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, is over 80% practically all the time. The exceptions are 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.

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

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 about 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, in particular with ionospheric disturbances at small distance scales. Other scenarios including Solar Maximum peak and large geomagnetic storms in Solar Maximum conditions are studied in Hernández-Pajares et al. (2000, 2001).

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[4] 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.