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Troposphere modeling for precise GPS rapid static positioning in mountainous areas

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Abstract
In global navigation satellite system precise positioning, double differencing of the observations is the common approach that allows for significant reduction of correlated atmospheric effects. However, with growing distance between the receivers, tropospheric errors decorrelate causing large residual errors affecting the carrier phase ambiguity resolution and positioning quality. This is especially true in the case of height differences between the receivers. In addition, the accuracy achieved by using standard atmosphere models is usually unsatisfactory when the tropospheric conditions at the receiver locations are significantly different from the standard atmosphere. This paper presents an evaluation of three different approaches to troposphere modeling: (a) neglecting the troposphere, (b) using a standard atmosphere model, and (c) estimating tropospheric delays at the reference station network and providing interpolated tropospheric corrections to the user. All these solutions were repeated with various constraints imposed on the tropospheric delays in the least-squares adjustment. The quality of each solution was evaluated by analyzing the residual height errors calculated by comparing the estimated results to the reference coordinates. Several permanent GPS stations of the EUPOS (European Position Determination System) active geodetic network located in the Carpathian Mountains were selected as a test reference network. The distances between the reference stations ranged from 64 to 122 km. KRAW station served as a simulated user receiver located inside the reference network. The user receiver ellipsoidal height is 267 m and the reference station heights range from 277 to 647 m. The results show that regardless of station height differences, it is recommended to model the tropospheric delays at the reference stations and interpolate them to the user receiver location. The most noticeable influence of the residual (unmodeled) tropospheric errors is observed in the station height component. In many cases, mismodeling of the troposphere disrupts ambiguity resolution and, therefore, prevents the user from obtaining an accurate position.

Keywords: precise positioning, troposphere delay modeling, GPS

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The troposphere is the part of the atmosphere extending from the Earth’s surface to about 20 km altitude containing most of the atmospheric water vapor. In satellite positioning, ranging signals are delayed when passing through the troposphere. It should be noted that the troposphere is a nondispersive medium for global navigation satellite system (GNSS) signals, so both pseudorange and carrier phase measurements are delayed by the same amount at both frequencies. The tropospheric effect
may be divided into dry (hydrostatic) and wet delays. The wet delay is induced by the water vapor in the atmosphere and causes \(\sim 10\%\) of the total tropospheric delay. It is much more variable and difficult to model and remove using standard atmosphere models, as compared to the hydrostatic part (Leick 2004, Hofmann-Wellenhof et al 2008). The tropospheric zenith total delay (ZTD) of GNSS signals reaches usually \(\sim 2\, \text{m}\) under the so-called standard atmosphere conditions at sea level, and the slant delay can approach up to 25 m at very low elevation angles (e.g., 5\(^\circ\)).

In GNSS precise positioning, double differencing of the observations is the common approach that allows for significant reduction of the correlated atmospheric effects. However, with increasing distance between the receivers, tropospheric errors decorrelate causing large residual errors affecting the carrier phase ambiguity resolution and ultimately, the positioning quality. This is especially true for baselines with large height differences between the receivers. This is due to a very high correlation, over a factor of 0.9 (Rothacher and Beutler 1998), of the troposphere with the height component, causing any unmodeled troposphere to contaminate mostly the estimated station heights, and to some extent, baseline length.

Nowadays, IGS (International GNSS Service) precise products, such as satellite orbits and clocks, Earth rotation parameters and ionosphere models, allow for considerable improvement of the GNSS positioning accuracy. However, the troposphere is still considered an ultimate accuracy-limiting factor in geodetic applications (when using double-frequency carrier phase GNSS observations). Its influence is particularly adverse in mountainous areas where large height differences between GNSS receivers are very common. The most popular approaches to troposphere modeling in differential GNSS positioning are:

1. neglecting the tropospheric effects (for very short baselines),
2. modeling the tropospheric effects using GNSS data from long (usually over one hour), static observational sessions; this requires long baselines (over 100 km),
3. using mathematical troposphere models,
4. using mathematical troposphere models supported by \textit{in situ} meteorological measurements,
5. applying numerical weather models to derive tropospheric delays,
6. modeling tropospheric delay at the reference station network and providing the interpolated corrections to the user.

The first four approaches do not give satisfactory results when processing stations with considerable height differences (hundreds of meters) using short sessions (e.g., 10 min or less). On the other hand, it is known that the tropospheric delay is relatively easy to model since its temporal correlation is long enough to do so in the least-squares adjustment positioning solution. However, for absolute troposphere delay estimation 30–60 min of GNSS data are usually required and the station separation should be over 100 km. Thus, the observational session duration of about 10 min may not be sufficient to separate the ZTD from the other estimates in the functional model. The reason is that too small a change in satellite geometry occurs during such a short session.

If permanent GNSS stations are available and they are properly distributed over the area of interest, then it is possible to take advantage of the network-derived ZTD. Further, if the coordinates of the permanent stations can be considered known, the procedure of the network solution becomes much easier to perform, even for long distances. In this case, the ZTD is estimated at the permanent stations surrounding the user location, along with the ionospheric delays in the same network solution, and interpolated to the user location (Zhang and Lachapelle 2001).

Motivation of the studies performed and presented in this paper can be summarized as follows.

(a) To develop and evaluate \textit{methodology} and \textit{algorithms} for a rapid static positioning technique suitable for long baselines,
(b) To test the applicability of different approaches to troposphere modeling in mountainous areas,
(c) To study the impact of the applied approach on the ambiguity resolution,
(d) To study the effect of the approach applied on the obtained position accuracy (particularly the height component).

This paper presents an evaluation of several approaches to the tropospheric delay modeling in rapid static applications over long baselines when using 10 min long observing sessions of dual frequency pseudorange and carrier phase GPS observations. Several permanent GPS stations of the ASG-EUPOS network (Polish part of European Position Determination System) located in the Carpathian Mountains were selected as a test reference network.

2. MPGps software

The test data processing was performed using in-house developed Multi-Purpose GPS Processing Software (MPGPS\textsuperscript{TM}), developed at The Ohio State University in cooperation with the University of Warmia and Mazury in Olsztyn (UWM). The software includes different processing modules: long-range instantaneous/OTF (On-The-Fly) RTK (Real Time Kinematic), rapid-static positioning, precise point positioning (PPP), multi-station DGPS (Differential GPS), ionosphere modeling and mapping and troposphere modeling. The software operates in static, kinematic and instantaneous modes and can provide solutions in the network as well as baseline modes.

The methodology and algorithms applied for the network-derived ZTD estimation used in the MPGPS\textsuperscript{TM} software are described in Kashani \textit{et al} (2005), Wielgosz \textit{et al} (2005), and Grejner-Brzezinska \textit{et al} (2007). For completeness, only
was analyzed (see figure 1). The data were divided into KATO, BUZD, NWTG and ZYWI with a 15 s sampling rate, baseline mode. The elevation cut-off angle was set to 15°. 78 sessions, each 10 min (40 epochs) long, were processed independently, one by one, in the single network solution that uses the dual-frequency pseudorange observations at lower elevations. As in surveying practice it is difficult to expect collecting GPS observations at lower elevations.


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3.1. Positioning solutions with and without tropospheric corrections

This section discusses the results obtained for two baselines, with the smallest and the largest height differences. The first baseline is KRAW–BUZD, 72 km long, with the height difference (ΔH) between KRAW and BUZD of 32 m. The second baseline is the 66 km long KRAW–NWTG, with ΔH of 380 m. These baselines were selected to present the analyses of two of the most extreme cases with the smallest and the largest ΔH in the analyzed test network.

The baselines were processed in the static mode using seventy-eight 10 min long sessions. Three approaches to troposphere modeling were tested, as indicated in the introduction:

(a) neglecting the troposphere (1a),
(b) applying the modified Hopfield model (Goad and Goodman 1974) with standard atmosphere parameters (1b),
(c) applying the network-derived absolute ZTD interpolated to the user location (four reference stations used here to derive a ZTD) (1c).

The results are provided in Table 2. The statistics included are the AR success rate in %, AR validation failure rate in %, and mean residuals for each coordinate component with their respective standard deviations (both in cm in the local horizon frame). It is shown that one cannot rely solely on double differencing of GPS observations in order to remove the tropospheric delays for medium-range baselines of 60–70 km in the case of both small and large station height differences.

The solution (1a) without tropospheric corrections is not acceptable, as only ambiguities in 23.0% and 38.7% of the sessions were fixed correctly for the KRAW–BUZD and KRAW–NWTG baselines, respectively. In addition 28.4% and 22.7% of false fixes (validation failures) occurred. Hence, the quality and the reliability of the position are not acceptable. The mean residuals of the height component reached 21.6 and 24.2 cm for the first and second baseline, respectively. The results obtained for the KRAW–NWTG baseline are shown in Figure 2 (coordinate residuals in the local horizontal frame). In the left panel, the black dots represent the results with incorrect fixes, the grey dots represent the correct fixes (green online). The black box in the center of the left panel represents ±2 cm threshold where all horizontal position residuals are expected. Two black lines in the right panel represent ±5 cm threshold where all height component residuals are expected to fall. It can be observed that almost all the residuals fall outside the required thresholds. Even the horizontal position was of very poor quality.
The second solution (1b) was obtained with tropospheric corrections derived from the modified Hopfield model. Standard atmosphere parameters were used in the model (temperature 18.5 °C, pressure 1013.25 hPa, relative humidity 50% at the sea level). The model takes station height into account, so, to some extent, it reduces the influence of different station heights. This approach allowed us to correctly fix the ambiguities for 93.2% and 92.0% of the sessions for the KRAW–BUZD and KRAW–NWTG baselines, respectively. Ambiguity validation failure rate dropped to 1.4% and 0.0%, respectively, for these baselines. This is a significant improvement in the ambiguity resolution results. The mean residuals of the height component dropped to +8.1 and −10.1 cm, respectively, representing a considerable improvement in the position quality. Figure 3 shows the coordinate residuals obtained with the second approach for the KRAW–NWTG baseline. The height component accuracy is still not acceptable for many of the surveying applications requiring cm-level accuracy of the vertical coordinate. However, the horizontal component residuals do not exceed ±4 cm threshold; hence this relatively simple approach assures good quality of the horizontal position and may be used in many applications. Note that only 10 min of GPS data were used in each session and the baseline lengths are ~70 km.

The third solution (1c) was obtained using the ZTD derived at the reference station network and interpolated to the user location. Station height differences were taken into account in the interpolation procedure. The resulting ambiguity success rate was very high and reached 97.3% and 98.7% for the KRAW–BUZD and KRAW–NWTG baselines, respectively. There were no ambiguity validation failures. There is also a noticeable improvement in the horizontal position quality (see table 2). However, the most evident improvement can be seen in the height component. The mean residuals dropped to only −3.9 and −2.0 cm for both baselines, respectively. It can be seen in figure 4 that most of the vertical component residuals fall within a ±5 cm limit for the KRAW–NWTG baseline. This approach has a clear advantage with respect to the two other approaches discussed above, as it utilizes the ZTD interpolated from the ‘true’ (estimated) delays derived at the reference station network from GPS observations.

3.2. Constrained solutions with ZTDs in the functional model

In the previous section, the tropospheric delays (from the modified Hopfield model or the network-derived ZTD) were used as corrections to the GPS observations and considered errorless. Below, a more elaborate solution is proposed.
ZTDs for the user or both the user and the reference station were included in the functional model as additional weighted parameters (see equation (1)). This approach was already applied in the reference network solution, where ZTDs were estimated for the reference stations. This allows for using the modified Hopfield (2b) or the network-derived ZTD (2c) as a priori values with proper constraints/weights in the adjustment, and therefore, accounting for their uncertainty. Please note that for baselines shorter than \( \sim 100 \) km, only relative ZTD estimation is feasible due to the correlation between the ZTDs at baseline ends.

In the first solution tested (2a), absolute ZTDs for both the reference station and user were treated as unknowns without any a priori information, and their constraints were completely released (all stations). Therefore, absolute ZTDs were estimated; however, due to short observational sessions and too short baseline (high correlation between ZTDs) their accuracy was not satisfactory. The results for the KRAW–NWTG baseline are presented in table 2. When comparing that solution to the one that neglects the tropospheric delays (1a), a clear improvement may be noted in both position quality and ambiguity resolution. The AR success rate was improved from 38.7\% to 93.3\% and the AR validation failure rate dropped from 28.4\% to 0.0\%. Figure 5 shows that coordinate residuals for the horizontal component fall within \( \pm 3 \) cm in the east direction and \( \pm 8 \) cm in the north direction (which is approximately the direction of the processed baseline). The residuals for the height component fall mostly within a \( \pm 12 \) cm threshold and their mean amounted to –1.1 cm, showing a clear improvement with respect to the results obtained with solution (1a).

Another solution analyzed here uses ZTDs evaluated from the modified Hopfield troposphere model as a priori values with constraints of \( \pm 5 \) cm for the user station (2b), and as fixed constraints (0.0 cm) for the reference station. Thus, a relative ZTD estimation was applied. In general, the relative ZTD estimation is recommended for baselines shorter than 100 km. In terms of AR, this solution is slightly better than (1b), where tropospheric delays from the modified Hopfield model were used just for correcting the observations. The AR success rate improved from 92.0\% to 96.\%, as compared to (1b). However, the vertical component accuracy is much better in this test. The mean of the residuals dropped from –10.1 cm (1b) to –2.0 cm (2b), as can be seen in figure 6.

The next approach tested was solution (2c) with ZTD from the reference network used as the a priori value in the user positioning solution. Since ZTD for the reference station was derived from GPS observations in the reference network solution, its value was fixed in the adjustment. However, ZTD interpolated for the user was constrained to \( \pm 2 \) cm, which we believe should properly reflect its accuracy. Note that ZTDs for the reference stations were fixed and, therefore, the relative ZTD estimation was applied. In terms of the AR performance, it can be concluded that the comparison of solutions (2c) and (1c) indicates that the AR success rate drops by 4\%. It may be the effect of released constraints, which in turn influences the validation results. In this case, the W-ratio test may provide slightly lower values, and hence a good solution may not pass the conservative validation threshold. The quality of the vertical position is better in terms of lower mean residuals, but at the price of higher scatter (table 2). Figure 7 shows that the scatter of the residuals in the height component is larger in (2c), as compared to (1c), which corresponds to the statistics in table 2. We believe that solution (1c) is slightly better, but the danger is that it cannot account for possible biases in the network-derived ZTD.

### 3.3. Multi-baseline solutions

When the measurements are taken within any permanent GNSS network (e.g., CORS), a multi-baseline solution may be used. It is expected that the results obtained with this approach should be generally better, since there are more observations available. Also, it is believed that the correlations between the baselines are easier to take into consideration (e.g. Hofmann-Wellenhof et al. 2008).

It is obvious that the multi-baseline solution, like the single-baseline approach described in the previous sections, may be augmented with a chosen method of tropospheric refraction mitigation. For the purpose of this paper, the three procedures above were implemented and tested: neglecting the delay altogether (for comparisons only), applying the modified...
Hopfield model and the network-derived ZTD. Further, the last approach was tested for two cases (also as previously): with and without constraints imposed on the ZTD.

All four baselines from the nearest permanent stations to the KRAW station (see figure 1) were selected and processed simultaneously; thus four four-baseline solutions were obtained and analyzed (table 2).

In the first solution tested, where the troposphere was neglected completely, the results can be summarized as follows (see table 2): ambiguity resolution success rate of 36.5% (similar value as obtained in other cases with troposphere neglected), mean coordinate residuals dN and dE on the level of 4 cm and mean dU 11.7 cm, with standard deviations of about 13 cm for all components. As expected, in the next solutions analyzed, all the results are much better. In the multi-baseline solution with the modified Hopfield model implemented, the AR success rate improved to 70.3%, the mean dE, dN are of the order of 1 cm, while the mean dU amounts to almost 7 cm (note the reverse sign in comparison with the previous solution, it seems the model ‘overestimates’ the correction). The best solutions were obtained with the network-derived ZTD (figures 8 and 9). The AR success rate is 95.9–97.3% for the approaches with ±2 cm constraints (user station) and fixed constraints, respectively, while all the other parameters are on the same level of quality. Perhaps only the mean dU can be distinguished, it amounts to −3.4 cm for the case of fixed constraints, and −1.5 cm (twice as good) for the case with ±2 cm constraints, but again, at the price of slightly bigger scatter of the heights obtained.

All the results for the multi-baseline solutions are given in table 2. Example plots of the solution with ZTD with fixed constraints are presented in figure 8. In addition, a height component comparison for fixed and constrained ZTD solutions are provided in figure 9.

4. Summary and conclusion

Table 2 provides a summary of all the tested solutions. The best approaches for a particular scenario are marked with bold font. It is confirmed that over distances of tens of kilometers double differencing of the GPS observations is not sufficient to remove tropospheric delays (1a). The remaining tropospheric residuals clearly hamper the AR process and corrupt the position quality. As can be seen, the best results are obtained by applying ZTD interpolated from the reference network (network-derived ZTD), regardless of using the constraints or not (1c and 2c). This approach is feasible anywhere where reference station networks are established. The modified Hopfield model (or any standard atmosphere model) may be applied (1b) in the absence of the network-derived ZTD, and
the results may be improved by constraining the user ZTD to, e.g., ±5 cm in the least-squares adjustment (2b). It is interesting to see that solution (2a) with no a priori knowledge of the tropospheric delays may also give acceptable results, at least for applications that do not require highest accuracy. Another interesting conclusion is that the results obtained for baselines with low and high ΔH give very similar results when applying the network-derived ZTD or the modified Hopfield model. It will be interesting to test the presented methodology on baselines with larger station height differences.

In the multi-baseline approach, again the best results are obtained for the case of the network-derived ZTD. Introducing small constraints (±2 cm) the solution may be regarded as slightly better than for the case with fixed constraints.

Future research will include application and testing of tropospheric delay models and mapping functions derived from advanced numerical weather models (NWM), e.g., GPT model, GMF and VMF1 mapping functions (Boehm et al. 2006a, 2006b, 2007), as long as wet and dry tropospheric delays derived from NWM like ECMWF (Fund et al. 2010) or from NWM supported with meteorological and GPS measurements (Bosy et al. 2010).

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