Improving accuracy of near real-time Precipitable Water Vapor estimation with the IGS predicted orbits

Yanxiong Liu[1] and Yongqi Chen

Dept. of LSGI, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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[1] The accuracy of estimated Precipitable Water Vapor (PWV) content in near real time using ground based GPS/Met strongly depends on the quality of GPS orbits. The impact of the predicted GPS orbits in IGS Ultra-rapid products on PWV estimation is investigated in this paper. A few satellites of poor orbits will contaminate the estimated PWV. In this study, variance ratios derived from adjusted GPS double difference carrier phase observations for different satellites are used to identify poor GPS orbits. By excluding or down weighting the measurements related to those poor satellites, the accuracy of PWV estimation can be significantly improved. *INDEX TERMS:* 1241 Geodesy and Gravity: Satellite orbits; 1243 Geodesy and Gravity: Space geodetic surveys; 3360 Meteorology and Atmospheric Dynamics: Remote sensing

1. Introduction

[2] The PWV derived from ground-based GPS/Met becomes an important and valuable data source in the Numerical Weather Prediction (NWP) [*Kou et al.*, 1996; *Smith et al*, 2000]. To meet the requirement of NWP update cycle (shorter than 2 hours), the GPS-derived PWV should be calculated in near real-time without a loss of accuracy. The high precision IGS rapid and final GPS orbits can satisfy the requirement of accuracy [*Bevis et al.*, 1992; *Rocken et al.*, 1993; *Coster et al.*, 1996; *Rocken et al.*, 1997; *Fang et al.*, 1998; *Kruse et al.*, 1999; *Liu et al.*, 1999], but are not available in real-time [*Springer*, 1999; *Fang et al.*, 2001]. The IGS predicted orbits, called the Ultra-rapid products, are appropriate for the real-time applications. However, the predicted satellite orbits sometime have orbital errors up to a few meters, which affect the PWV estimation with more than 2 mm errors.

[3] Several authors have developed methods to reduce the effect of orbital errors on the PWV estimates [e.g., *Dodson and Baker*, 1998; *Kruse et al.*, 1999; *Ge et al.*, 2000; *Ge et al.*, 2002]. Two approaches are identified: selecting or weighting GPS observations according to a so-called orbital accuracy code in the orbit file; and re-estimating the orbit parameters from a regional GPS network [*Ge et al.*, 2000]. It has been showed that the orbital accuracy code sometimes is not a reliable accuracy indicator [*Ge et al.*, 2000; *Ge et al.*, 2002]. Re-estimating the orbital parameters requires the real-time data transmission in a regional network (e.g. 2000 × 2000 km). Most GPS stations do not provide data in near real-time. Moreover, the geometry of a local small GPS network, such as Hong Kong multi-function GPS array covering area of 50 × 60 km, cannot permit the orbit re-estimation due to the similar coefficients in the matrix for the solution of orbital elements (ill-conditioned problem). In this study we propose an alternative approach to identify the satellites with poor predicted orbits. The viability of the proposed approach is tested with real examples.

2. Residual Analysis for the Identification of Large Orbital Errors

[4] For the PWV estimation, the coordinates of GPS stations are often accurately known, and so are the baselines between them. In addition, when high quality GPS receivers and Choke ring antennas are deployed within a network, the observation noises (errors) and multi-path effects are expected to be small. Moreover, atmospheric delays can be well modeled or eliminated in a local GPS array. Therefore, the residuals of observations after data processing should mostly reflect the orbital errors of a satellite. In this study we use the estimated variance of observations for each satellite to represent the quality of its orbit.

[5] The carrier phase observation ϕ can be written as

$$\lambda\phi = \rho + d_{atm} + d_{clock} + d_{orb} - \lambda N + d_{noise}. \quad (1)$$

where λ is the wavelength, ρ the geometric distance between the receiver and a satellite, and N is the ambiguity. Assuming that the observation noise d_{noise} is small, and both the atmospheric delay d_{atm} and clock error d_{clock} can be well modeled or eliminated after double differencing, the double difference observation equation between two stations and two satellites is given by

$$V = AX - \left(\rho^{ij} - \lambda\phi^{ij}\right). \quad (2)$$

where V is the residual of "observation" (double difference), A is the coefficient matrix, X is the unknown ambiguity, ϕ^{ij} the double difference of the carrier phase observations between satellite i and j, and ρ^{ij} is the double difference of the geometric distances, which can be computed using the coordinates of stations and satellite orbits. The second term in the right hand side of equation (2) is treated as "observations" in the adjustment. If there is a large error in a satellite's orbit, the corresponding observations will contain an outlier,

$$\varepsilon\varepsilon = d^{i}_{orb} - d^{i}_{orb}. \quad (3)$$

[6] An outlier detection technique can then be used to locate the satellite with an erroneous orbit. Assuming that

[1]Now at GFZ, Telegrafenberg A17, D-14473 Potsdam, Germany.

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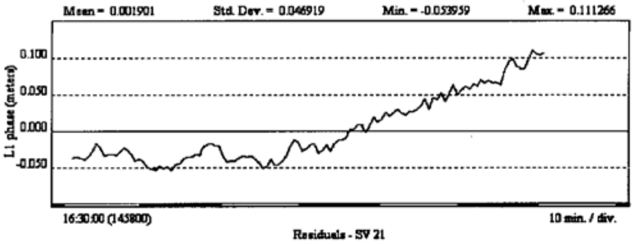

Figure 1. The residual distribution of the observations to Satellite 21.

the reference satellite *j* does not have large orbital error, the estimated residuals will reflect the effect of large orbit error of satellite *i*. After data processing (adjustment), one can calculate the variance σ_0^2 from all the residuals with degrees of freedom df_0, and the variance σ_i^2 with the degrees of freedom df_i from the residuals related to satellite i. We propose the use of following test to identify the satellite with large orbital error. Let

$$F = \sigma_i^2/\sigma_{0i}^2. \quad (4)$$

where σ_{0i}^2 is the variance without the observations to satellite i and computable from

$$\sigma_{0i}^2 = \left(df\sigma_0^2 - df_i\sigma_i^2\right)/df_{0i}. \quad (5)$$

with degrees of freedom df_{0i} being

$$df_{0i} = df_0 - df_i. \quad (6)$$

[7] The variance ratio in equation (4) follows approximately a F-distribution with degrees of freedom being df_i for numerator and df_{0i} for denominator. For a given significance level α, one can calculate its critical value F_α. If $F > F_\alpha$, the predicted orbit for satellite i may contain large errors.

[8] Before the calculation of the PWV, the above statistical test is performed. The computation takes only a few minutes, which makes the algorithm suitable for near real-time GPS meteorology applications.

[9] The proposed algorithm was tested using GPS data collected at two Hong Kong GPS stations with baseline length 25 km. Two example sets of GPS observations with one-hour duration each in March 5 2001 were processed using software Trimble Geomatics Office V1.0. The first example (the first set of data) in Figure 1 shows the residual distribution (L1 phase) of SV 21 (SV17 as a reference satellite) for the period 16:30–17:30 UTC. The estimated standard deviation without inclusion of the observation to satellite SV21 is 0.0344 m, and the corresponding standard deviation for SV21 is 0.047 m. The statistic $F = 0.047^2/0.0344^2 = 1.87$. At a significance level of 0.01, the critical value of F is 1.47. Since $F > F_\alpha$, the predicted orbit for SV21 may contain large errors. Indeed, a comparison of the Ultra-Rapid orbit with the IGS final orbit indicated that average orbital error is 9.3 meter during this period.

[10] Another example (the second set of data) in Figure 2 gives the residual distribution for the satellite SV23 during the period 13:30–14:30 UTC. The estimated standard

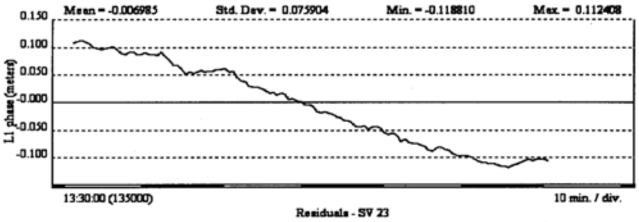

Figure 2. The residual distribution of the observations to SV 23.

deviation σ_{0i} is 0.050 m meter, and σ_i for SV 23 is 0.076 m. The test statistic F = 2.31 is larger than the threshold value 1.47. Also when compared to the IGS precise orbits, the average orbit error is 5.3 m.

3. Impact of Orbital Error on PWV Estimates

[11] To investigate the impact of "bad" satellite orbits on the PWV estimates, we used the data collected at six Hong Kong stations and an IGS station-SHAO, and GAMIT V10.05 software. In the processing, SHAO station was held fixed, and the other sites were tightly constrained to 1 and 2 cm in the horizontal and the vertical, respectively. To use all possible observations, the cutoff angle of elevation was set to 10 degree. One PWV parameter per hour was modeled and the variation of PWV was assumed to be a Gauss-Markov process with 2 cm/$\sqrt{hr}$. In estimating PWV, the satellite orbits were fixed. For comparison, the results using the IGS final orbits were used as reference (IGS). The results using the ultra-rapid orbits without bad satellites removed (IGU) and with bad satellites removed (IGUU) were computed and compared with IGS.

[12] We used one-month of GPS data to test our methodology, from March 1 to March 31, 2001. We found large errors in the IGU orbits for March 5 only, which are confirmed by comparing them with the IGS final orbits. We compared IGS and IGU for the whole month. The results show that the mean errors of SV19, SV21 and SV23 are 2.33 m, 3.97 m and 3.78 m on March 5, respectively, but the others are mostly about 0.5 m.

[13] The PWV comparison results for March 5, 2001 at four local sites are displayed in Figure 3. The solid lines with small circles represent the PWV differences between

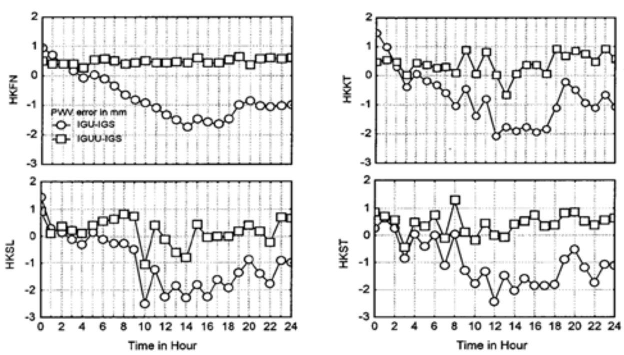

Figure 3. The comparison of the differences of estimated PWV with and without bad satellites in Ultra-rapid orbits.

Final orbits (IGS) and Ultra-rapid orbits (IGU). Their differences are in 2 mm to 3 mm, bigger than 0.5 mm under normal conditions. This is due to the large predicted orbit errors during this period. If the bad satellites in the Ultra-rapid orbits are removed, the corresponding PWV estimations (IGUU) are in good agreement with those using final orbits. The solid lines with small squares stand for their differences. Most of them are distributed around 0.4 mm.

[14] Because the four stations are only about 20 km apart, the orbital errors have nearly the same effect on the PWV estimates, as shown in Figure 3. We also reckon from this figure that over 2 mm PWV error will be produced when the orbital error is larger than 2 meter. It is a quite big error for the GPS meteorology application.

4. Conclusion

[15] Orbital errors are the main source of error for the near real-time PWV estimation. The IGS Ultra-rapid orbits are currently the most accurate predicted orbits for real-time GPS application. Their accuracies are better than 0.5 m when compared with IGS final orbits. However, the predicted orbits can sometimes have an error up to a few meters for a satellite which may not be reflected by the accuracy code. Thus, the detection of a large orbital error is important in estimating PWV. The proposed statistical testing based on variance ratios is simple and can effectively detect anomalous satellite orbits as demonstrated through two examples.

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Y. Liu and Y. Chen, Dept. of LSGI, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.