DETERMINATION OF GPS HEIGHT WITH INCORPORATION OF USING SURFACE METEOROLOGICAL MEASUREMENTS

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ABSTRACT Although the positioning accuracy of the Global Positioning System (GPS) has been studied extensively and used widely, it is still limited due to errors from sources such as the ionospheric effect, orbital uncertainty, antenna phase center variation, signal multipath and tropospheric influence. This investigation addresses the tropospheric effect on GPS height determination. Data obtained from GPS receivers and co-located surface meteorological instruments in 2003 are adopted in this study. The Ministry of the Interior (MOI), Taiwan, established these GPS receivers as continuous operating reference stations. Two different approaches, parameter estimation and external correction, are utilized to correct the zenith tropospheric delay (ZTD) by applying the surface meteorological measurements (SMM) data. Yet, incorrect pressure measurement leads to very poor accuracy. The GPS height can be affected by a few meters, and the root-mean-square (rms) of the daily solution ranges from a few millimeters to centimeters, no matter what the approach adopted. The effect is least obvious when using SMM data for the parameter estimation approach, but the constant corrections of the GPS height occur more often at higher altitudes. As for the external correction approach, the Saastamoinen model with SMM data makes the repeatability of the GPS height maintained at few centimeters, while the rms of the daily solution displays an improvement of about 2–3 mm.

KEY WORDS: GPS, ZTD, WVR

1. INTRODUCTION

Space-based geodetic systems, especially the Global Positioning System (GPS), have been widely utilized in recent decades. GPS technology has been applied to the fields of Plate Boundary Observatory (PBO), crust deformation and land survey. Since the positioning accuracy of the advanced data analysis schemes is in the level of 1–2 mm in horizontal coordinates, and 5–10 mm in vertical coordinates (GPS height) [Johansson et al., 1998; Bock and Doerflinger, 2000], one of the research objectives in this field is to improve the GPS height. The low accuracy in GPS height, compared with the horizontal coordinate, has two major causes, the theoretical limit of the satellite geometric distribution and the tropospheric path delay, especially due to water vapor (or wet path delay) [Davis et al., 1985; Dodson et al., 1996; Emardson and Jarlemark, 1999; Bock and Doerflinger, 2000; Liou et al., 2001].

Most GPS data analysis procedures utilize double differencing to reduce the clock and orbit errors. Carrier phase ambiguities, cycle slips, and clock errors can be repaired by processing pseudo-range signals and triple differenced phases, while ionospheric delay can be corrected by modeling or dual frequency combinations. However, the dual-frequency GPS scheme still suffers from path delay of the troposphere associated with inhomogeneity and variability of water vapor. An 1 mm error in the zenith tropospheric delay may generate biases of 2.6–6.5 mm in station height at various cut-off angles of 5°–25° [Santerre, 1991].

Two different tactics, parameter estimation and external correction, are undertook to resolve the troposhperic effects [Bock and Doerflinger, 2000]. The parameter estimation approach requires the a priori values of the ZTD from the empirical meteorological models with "standard (constant) atmosphere value" (SAV) [Tregoning and Herring, 2007] data or SMM data. The residual of the parameters in the a priori ZTD is then estimated using the least-squares method. The a priori ZTD with SAV data is adopted conventionally in GPS data analysis. Some special instruments, such as water vapor radiometer, and several general surface meteorological instruments at the GPS receiver sites, can be employed for external correction. The SMM data incorporated with the empirical meteorological model is served as the measured ZTD in the GPS data analysis.

2. DATA COLLECTION

The GPS data with a daily survey time of 24 hours were obtained from 5 GPS tracking stations operated by the MOI from day-of-year (DOY) 131 to 210 in 2003. The final precise ephemeris (SP3 file) and Earth rotation parameters (ERP file) were gathered from the IGS. The phase center of the antenna was provided by the U.S. National Geodetic Survey (NGS). As in Santerre [1991], the effects of solid earth tide and ocean tide were kept within few centimeters. In this study, both types of tide have been corrected from the solid earth tide [McCarthy, 1996] and the ocean tide of the GOT00.2 model [Scherneck, 1991]. The ocean tide models were obtained from the website http://www.oso.chalmers.se/~loading/, maintained by the Center for Astrophysics and Space Science in Sweden.

3. METHODOLOGY

The Bernese software V5.0 developed by the Institute of Astronomy University of Berne is utilized in the data processing for the data analysis. The ambiguity resolution algorithm of the double-difference equations is Quasi Ionosphere-Free (QIF). In addition, the data processing is performed by the Bernese Processing Engine (BPE).

The structure of the methodology, with different procedures and meteorological data, is presented in Figure 1. There are total of 5 results, numbered from (1) to (5), in this figure. The procedures are performed with different data sets. One data set is obtained from SAV data, and the data employed (pressure, temperature and relative humidity) for a priori models are followed the height-dependent principle [Dach et al., 2007]. The other data set is gained from data observed at the GPS receiver sites.

Two approaches, i.e. parameter estimation and external correction, are adopted separately to obtain the ZTD. Results (1), (2), and (3) are obtained by the parameter estimation approach, with 24 tropospheric parameters in each case. Result (1) in Figure 1 is acquired from the conventional method that the a priori ZTD values are derived from the SAV data with a priori dry model (Saastamoinen Dry Part with Dry Niell Mapping Function [Niell, 1996]). The results of (2) and (3) are attained from the SMM data with different a priori models (Saastamoinen with Niell Mapping Function [Niell, 1996]), then the residual of ZTD are estimated using the least-squares method subsequently. The different cut-off-angles in the GPS data are also utilized in this part. Results (4) and (5) are obtained by the external correction approach, in which the ZTD is corrected directly with the Saastamoinen model, and are based on the GPS data with different cut-off-angles.

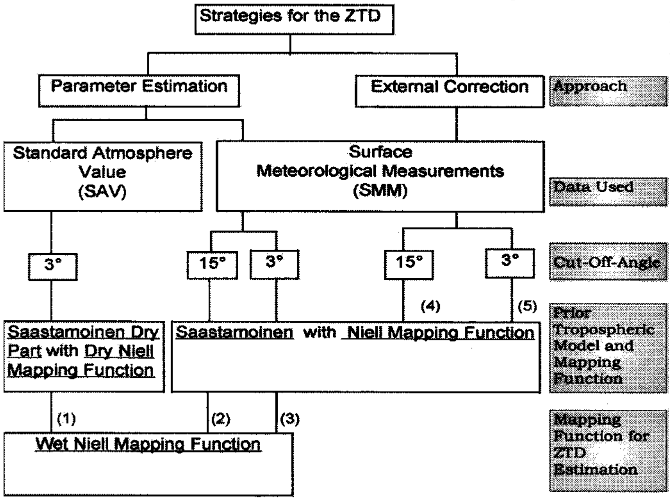

Figure 1. The structure of the strategies for the ZTD.

4. RESULTS

Two aspects are obtained when using SMM data. First, the GPS height is estimated with the parameter estimation approach. The comparison between the results (1) and (3) is the outcome by different a priori ZTDs obtained from the SAV and SMM data for each station. Figure 2 presents the difference in GPS height between the two approaches. The proposed approach based on least-squares and the SAV data or SMM data makes the priori ZTDs different. The trends in the figure show only small changes for every station. The differences between results (1) and (3) are only a few millimeters. The differences between the maximum and the minimum of the YMSM, FLNM, KDNM, and PKGM are 7.7 mm, 7.2 mm, 8.1 mm and 8.4 mm, respectively. The rms of GPS height is similar for all solutions. The SMM data cannot represent the entire tropospheric profile. Therefore, the SMM data in the parameter estimation approach makes only few millimeters of differences and stables the repeatability change in sub-millimeters.

However, Figure 2 reveals one important issue. According to the vertical profile of the water vapor, a GPS station at a higher altitude is less affected by the water vapor. The GPS height of the YMSM, FLNM, KDNM and PKGM are about 784 m, 138 m, 58 m and 42 m, respectively. The percentages of the minus differences values in the figure are 69.5%, 57.6%, 50.9% and 30.5%, respectively. The amount of the minus difference increased with the GPS height. This phenomenon indicates that the a priori ZTDs are closer to the actual atmospheric situation, and that the trend of corrections on the GPS height is more accurate. From the viewpoint of the a priori value in GPS height estimated, as Tregoning and Herring [2006] stated, "Not using accurate surface pressure leads to errors in the a priori ZHD values which, in turn, corrupt the estimates of station heights and ZTD values in GPS analyses".. The statement is focused on the SAV data used in the conventional strategy. Nevertheless, the viewpoint is still suitable when using the SMM data. The a priori ZTDs derived from the SMM data are closer to the true atmospheric situation. The reduced effect from the water vapor increases the importance of correcting the GPS height.

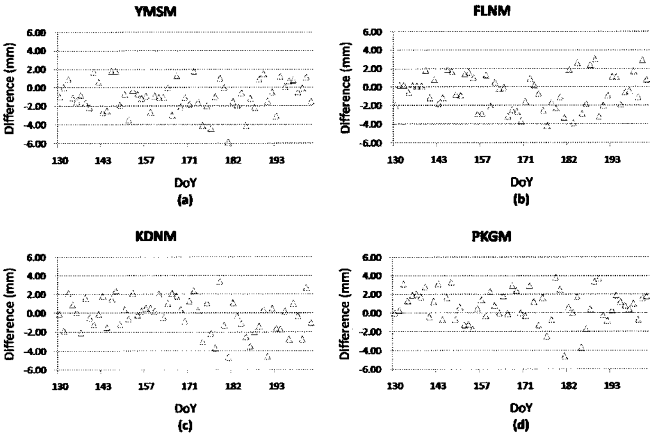

Figure 2. The difference of the GPS heights (result (1) minus result (3)) between the SMM data with or without a priori ZTD in parameter estimation approach.

The GPS height is also estimated with the external correction approach. Results (1) and (5) are obtained from the conventional strategy and an external correction approach. For result (5), the SMM data is introduced into the Saastamoinen model to attain the ZTD, which the direct correction is applied. The difference between the averages of results (1) and (5) for the YMSM, FLNM, KDNM and PKGM reached 13.2 cm, −3.3 cm, 4.1 cm and 8.4 cm, respectively. Although this approach produces a large variation in the GPS heights, it improves the daily rms by about 2–3 mm.

"The results of this approach were never really exciting. They often turned out to be disastrous when processing data from small networks: Instead of having height repeatability of a few millimeters, only centimeters were obtained," according to Beutler et al. [1989]. This observation is consistent with the results in the Table 1. The standard deviation (Std. Dev.) of the GPS heights during the observing time shows that the SMM data make the outcome unstable, as occurred in the results. A GPS station at a higher altitude is less affected by the water vapor. The ZTDs, which are corrected from the Saastamoinen model, are closer to the actual results, and the trend of corrections on the GPS height is more consistent. The standard deviation of the YMSM station located at the highest altitude in the network is lower than that of other stations and the correction values for the GPS height are the steadies.

Table 1. The averages and standard deviations of daily solution in GPS heights.

GPS height		YMSM	FLNM	KDNM	PKGM
Average (m)	**Result (1)**	784.0617	138.5280	58.3029	42.8712
	Result (5)	783.9295	138.5610	58.2622	42.8253
Std. Dev. (mm)	**Result (1)**	11.2	11.5	12.7	10.7
	Result (5)	57.5	80.8	111.4	92.6

In GPS data processing, the threshold angle can be used to eliminate poor measurements resulting from multiple paths or bad signals. However, a higher cut-off-angle usually leads to a poorer geometric distribution of satellites, thus leading to the imprecision in GPS heights. This study changes the cut-off-angle from 3° to 15°.

Comparing the GPS heights using either parameter estimation (result (2) and result (3)) or external correction (results (4) and (5)) reveals that the averages and the standard deviation of each GPS station are very similar. Table 2 lists the maximum and the minimum differences in GPS height between different cut-off-angles. The differences of varied cut-off-angles are about ±1mm at the GPS stations when using parameter estimation, which have lesser values in comparison with the external correction approach. For the external correction approach although the values in the YMSM and PKGM stations are more unstable according to Table 2, their average of the difference is only about 3 mm. Increasing the cut-off-angle does not change the precision of the GPS height in this study. The Niell mapping function for SMM data in the study is clearly stable.

Table 2. The difference of GPS heights between the different cut-off-angles when the SMM data used in parameter estimation and external correction approach.

Difference of GPS height		YMSM	FLNM	KDNM	PKGM
Parameter estimation (result (2), 15 degree) minus (result (3), 3 degree) **(mm)**	**Max.**	5.8	9.9	8.9	9.3
	Min.	-8.4	-3.0	-3.4	-6.7
	Average	-1.7	-0.1	1.3	0.1
	Std. Dev.	2.4	2.1	2.6	3.1
External correction (result (4), 15 degree) minus (result (5), 3 degree) **(mm)**	**Max.**	14.6	1.3	3.2	6.3
	Min.	-5.8	-3.6	-5.1	-14.7
	Average	3.5	0	-0.6	-3.1
	Std. Dev.	4.4	0.7	1.4	3.9

The use of SMM data presents another important issue. If the error in the pressure measurement is found in the daily meteorological measurement file, it significantly and adversely affects the accuracy. Several epochs show incorrect measurements in the daily file. The inaccuracy of the GPS height is up to few meters, and the rms of the daily solution ranges from millimeters to centimeters, regardless of the approaches adopted.

5. CONCLUSIONS

GPS is a microwave technique which makes it necessary to perform the tropospheric zenith corrections [Rothacher and Beutler, 1998]. This investigation focuses on the effect of troposphere on GPS height, and uses SMM data in both parameter estimation and external correction methods to correct the tropospheric zenith delay.

In the parameter estimation approach, the effect on GPS height is not obvious when using SMM data. However, the trend of corrections on the GPS height is more consistent at higher altitudes, due to accurate surface meteorological measurement and less wet delay.

In the external correction approach, the accordance of the correction still appears in the YMSM station. The Saastamoinen model based on SMM data stabilizes the GPS height within a few centimeters. The rms of the daily solution is improved by about 2–3 mm, and the variations of the average GPS heights are reached to several centimeters.

The cut-off-angle does not affect the precision of the GPS height. The experimental results indicate that the Niell mapping function for using SMM data in the study is stable.

Incorrect pressure measurements lead to poor accuracy. The inaccuracy of the GPS height can reach several meters whereas the rms of the daily solution ranges from a few millimeters to centimeters, no matter what the approach is used.

Analytical results show that higher GPS stations generally have smaller standard deviations for height determination. Thus, the variability of GPS height increases with the total water vapor burden [Liou et al., 2001]. In the future, high-altitude GPS stations should be applied with SMM data to investigate this phenomenon properly.

Acknowledgment. This work is supported by a grant from the Ministry of Interior (MOI) of Taiwan, and National Science Council (NSC) of Taiwan (NSC 95-2119-M-008-036).

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