A STUDY OF TROPOSPHERIC EFFECT ON HIGH PRECISION GPS HEIGHT DETERMINATION

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ABSTRACT: Constantly enhancing positioning accuracy by the Global Positioning System (GPS) technique is of great importance, but challenging, especially after the GPS positioning technique has been improved considerably during the past two decades. The associated main error sources have been reduced substantially, if not eliminated. Troposhpeic influence with its highly temporal and spatial variability appears to be one of the major error sources. It is hence an increased interest among GPS researchers to reduce the tropospheric influence or delay. Two techniques have been commonly implemented to correct the tropospheric impact. The first technique, known as parameter estimation, characterizes the path delay with empirical models and the parameters of interest are determined from the GPS measurements. The second strategy, termed as external correction, involves independent path delay measurements. The present study is an integration of both techniques in which the parameter estimation as well as external correction are used to correct the path delay for 110~210 km range baselines. Twenty-four parameters have been obtained in 24 hours solution by setting the cutoff angle at 3 and 15 degrees for parameter estimation strategy. Measurements from meteorological instruments and water vapor radiometer (WVR) are applied in the GPS data processing, separately, as an external strategy of present research work. Interesting results have been found, indicating more stable repeatability in baseline when the external correction strategy is applied especially with the inclusion of WVR observations. The offset of an order of 1 cm is found in the baselines determined by the two strategies. On the other hand, parameter estimation exhibits more stable in terms of GPS height repeatability. The offset in the GPS height determined by the two strategies is on the order of few centimeters.

KEY WORDS: GPS, Troposphere, Total delay

1. INTRODUCTION

With the present state-of-the-art of the GPS data analysis schemes in geodesy, positioning accuracy is on the level of 1–2 mm in horizontal coordinates and 5–10 mm in the vertical coordinates (Bock and Doerflinger, 2000; Johansson et al., 1998; Liou et al., 2000). There are two major reasons responsible for the less accuracy in the vertical coordinate than horizontal coordinate. The first one is due to a theoretical limit of the satellite geometric distribution in sky since observations are only made within a minimum elevation angle (typically about 15°). The other one is due to tropospheric effect, especially due to water vapor (or wet path delay) (Bock and Doerflinger, 2000; Davis et al., 1985; Dodson et al., 1996; Emardson and Jarlemark, 1999; Liou et al., 2001). The influence of surface meteorological data on tropospheric zenith delay has been reported in the literature (Beutler et al., 2001). It must take special care in the regions with highly variable and abundant water vapor in the air, such as in the tropical and subtropical areas.

In most GPS data analysis procedures, the method of double differencing is used to reduce clock and orbit errors. Carrier phase ambiguity, cycle slips, and clock errors can be fixed by processing pseudorange signals and triple differenced phases, while ionospheric delay can be corrected by modelling or dual frequency combinations. The main error source left in the station height by the dual frequency GPS scheme is path delay of the troposphere associated with inhomogeneity and variability of water vapor. An l-mm error in zenith tropospheric delay may produce biases of 2-6 mm in station height for elevation cutoff angles between 5° and 25° (Santerre, 1991).

In general, empirical meteorological models are used to derive atmospheric path delay of the GPS signal with enough accuracy for most geodetic applications, while they are insufficient for the applications with high precision needs. To meet the needs, two strategies that are used include parameter estimation and external correction methods. For the external correction method, some special and expensive instruments must be applied, such as water vapor radiometer (WVR). Normally, the parameter estimation method is adopted for correcting the tropospheric effects in the GPS data analysis. In this study, the parameter estimation approach and external correction are applied to study the effect on the GPS height determination.

2. TROPOSPHERIC DELAY

When an electromagnetic wave propagates through the atmosphere, it is continuously refracted due to the varying index of refraction of the air along the ray path. There are two kinds of effects on a ray path: bending and retarding. Both of them produce an excess path length with respect to propagation in vacuum. Usually, the excess path length from bending is about 1 cm at 15°, which is usually neglected (Ichikawa, 1995). Excess path length due to signal retarding in the troposphere (tropospheric path delay) is expressed as (Davis et al., 1985)

$$\Delta L = \int [n(s) - 1] ds = 10^{-6} \int N(s) ds \qquad (1)$$

where $N = (n-1)\times10^6$ and n are the refractivity and index of refraction of the air at a point s along the ray path, respectively. Refractivity of air is usually described by the empirical formula (Thayer, 1974)

$$N = k_1 R_d \rho_d + k_2 R_w \rho_w + k_3 R_w \frac{\rho_w}{T} \qquad (2)$$

where k_i represents the refractivity constants, ρ_d is the density of dry air, ρ_w denotes the density of water vapor, R_d and R_w are gas constants, and T is the temperature.

Some assumptions are usually adopted for computing the path delay. For example, one assumes that path delay in an arbitrary direction is related to path delay at zenith or zenith tropospheric delay (ZTD) by mapping functions (or tropospheric obliquity factor) (Davis et al., 1985):

$$\Delta L = \Delta L_h^z \times m_h(\varepsilon) + \Delta L_w^z \times m_w(\varepsilon) \qquad (3)$$

where ΔL_h^z and ΔL_w^z are hydrostatic and wet delays at zenith, respectively, $m_h(\varepsilon)$ and $m_w(\varepsilon)$ are mapping functions, and ε is the elevation angle. A number of mapping functions have been proposed. The simplest model for both hydrostatic and wet components is $1/\sin(\varepsilon)$.

From (2), delays at zenith become

$$\Delta L_h^z = 10^{-6} k_1 R_d \int \rho dz \qquad (4)$$

$$\Delta L_w^z = 10^{-6} k'_2 R_w \int \rho_w dz + 10^{-6} k_3 R_w \int \frac{\rho_w}{T} dz \qquad (5)$$

where $k'_2 = k_2 - (R_d / R_w) k_1$.

The zenith hydrostatic delay (ZHD) ΔL_h^z is about 2.30-2.60 m at sea level. It represents 90–100 % of the ZTD. The zenith wet delay (ZWD) ΔL_w varies roughly from 0 to 40 cm between the poles and the equator, and from a few cm to about 20 cm during the year at mid-latitudes. Note that the first integral in (5) represents only about 0.1 % of the ZTD (Bock and Doerflinger, 2000). The variation of ZTD must be accurately and carefully monitored. The effect of a 1 mm error in ZTD will result in a bias of nearly 2–6 mm in GPS station height, depending mainly on the elevation cutoff angle (5–25°) and site latitude (Santerre, 1991).

3. DATA COLLECTION AND STRATEGIES

3.1 Data Collection

In the study, the GPS data with surveying time 24 hours a day were collected from GPS tracking Stations operated by the Ministry of Interior (MOI) in Taiwan. The WVR and the surface meteorological equipments take measurements simultaneously. Three baselines (PKGM-KDNM, PKGM-FLNM, PKGM-YMSM) were measured in sequence and they were shown as Figure 1.

In the GPS height determination, the final precise ephemeris (SP3 file) from the IGS and phase center of antenna provided by U.S. National Geodetic Survey (NGS) were used. According to (Beutler et al., 2001), the effects of solid earth tide and ocean tide are of the order of a few centimeters. In this study, both types of tide have been corrected by using the solid earth tide (McCarthy, 1996) and the ocean tide of the GOT00.2 model (Scherneck, 1991). Both tide models are computed by the Center for Astrophysics and Space Science in Sweden (http://www.oso.chalmers.se/~loading/).

The Bernese software V5.0 developed by the Institute of Astronomy University of Berne is used in the data processing. The ambiguity resolution algorithm of the double difference equations is Quasi Ionosphere-Free (QIF). The data processing is performed by the Bernese Processing Engine (BPE). The coordinates of the 4 IGS stations (GUAM, NTUS, USUD and WUHN) are fixed.

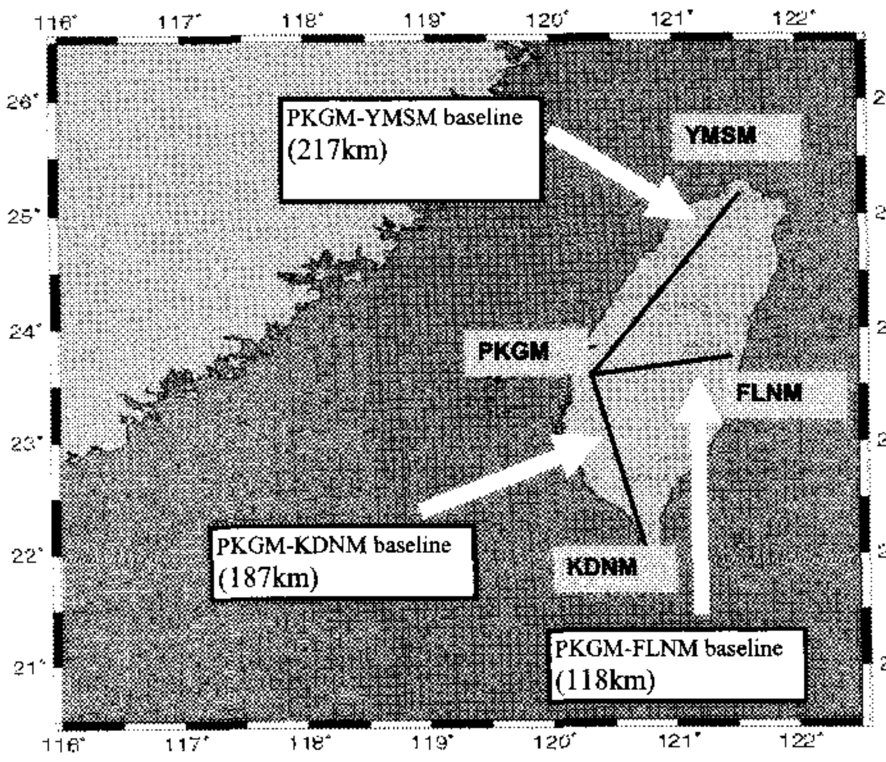

Figure 1. The geographic locations of the GPS stations.

3.2 Strategies of the Tropospheric Delay Correction

Two methods are commonly adopted to correct the tropospheric path delay in GPS. In the first strategy, the path delay is described with empirical models and parameters of interest are estimated from GPS measurements. This approach is generally called parameter estimation. In the second strategy, independent measurements of path delay are applied to GPS data processing for solutions. This approach is called external correction. In this study, the parameter estimation and external correction are used to correct the path delay for the baselines in the range of 110~210 km. For the parameter estimation strategy, 3- and 15-degree cutoff angles are used and the Niell model is applied as *a priori* model. Twenty-four parameters are obtained in 24 hours solution. For the external correction strategy, measurements from meteorological instruments and WVR are applied in the GPS data processing, separately. The structure of the strategies instruction is shown as Figure 2.

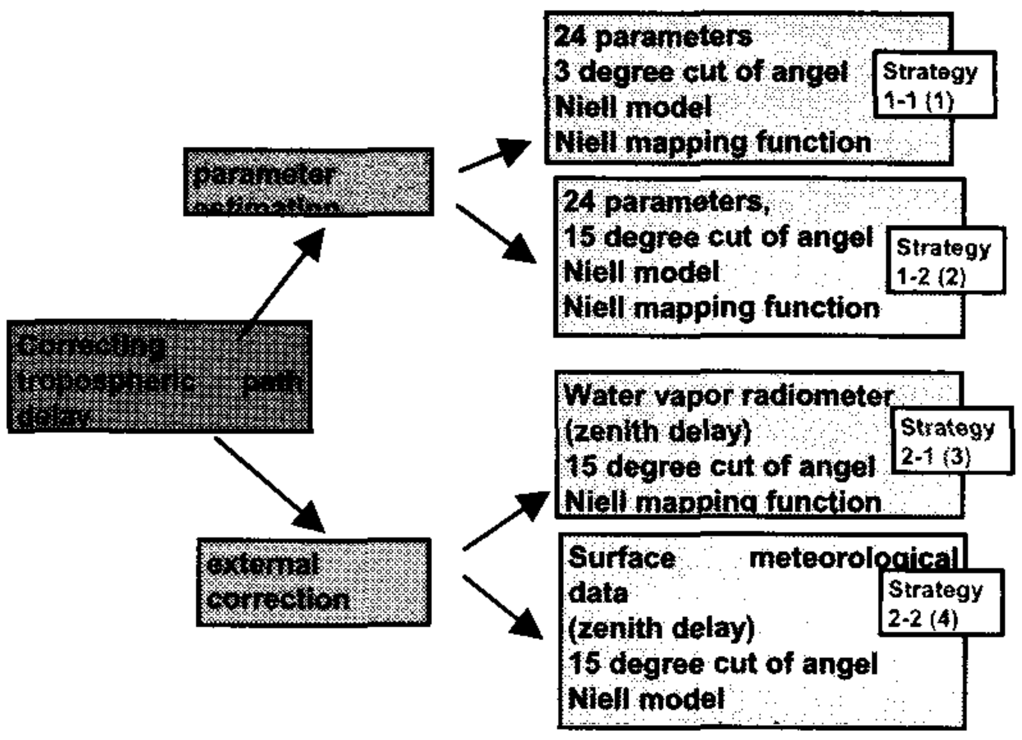

Figure 2. Structure of the strategies instruction.

4. RESULTS

In the study, the results with incorporation of the WVR measurements in data processing are considered as reference.

For the repeatability of the baselines, the standard deviations of the baselines using the strategies of the external correction with the data for the cut-off angle of 15 degrees, either from WVR or surface meteorological instruments, are superior to those using the strategy of the parameter estimation. When only the strategies of the parameter estimation were used, the better results were obtained with the lower cut-off angles.

When the coordinate of the PKGM station was fixed in the data processing, the GPS heights of the other endpoints for the three different baselines are shown in Figure 3, Figure 4 and Figure 5, respectively, with four different methods, and the comparisons of the GPS heights are shown in Table 1. The difference of the GPS heights between the strategy 1-2, widely used in the GPS data processing, and the other strategies were also computed and shown in Table 2. Although the standard deviations of the GPS heights with the strategy of the external correction show little difference, only few millimeters, from those with the strategy of parameter estimation, the GPS heights were greatly reduced by the order of centimeter when the external correction data were used,. The result represents that the total delay correction with the strategy of the parameter estimation still has plenty of room for improvement.

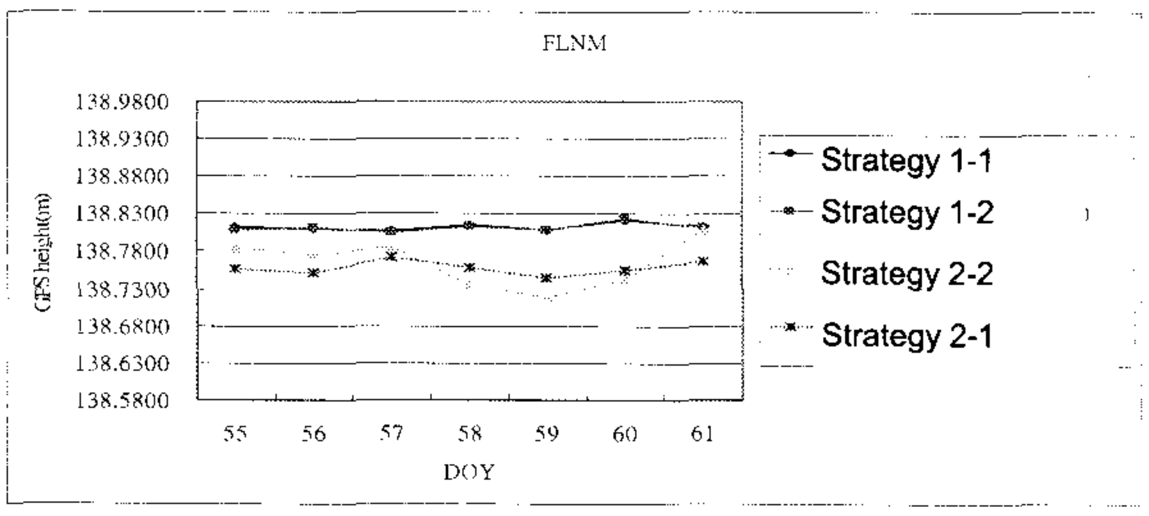

Figure 3. The GPS height of the FLNM station.

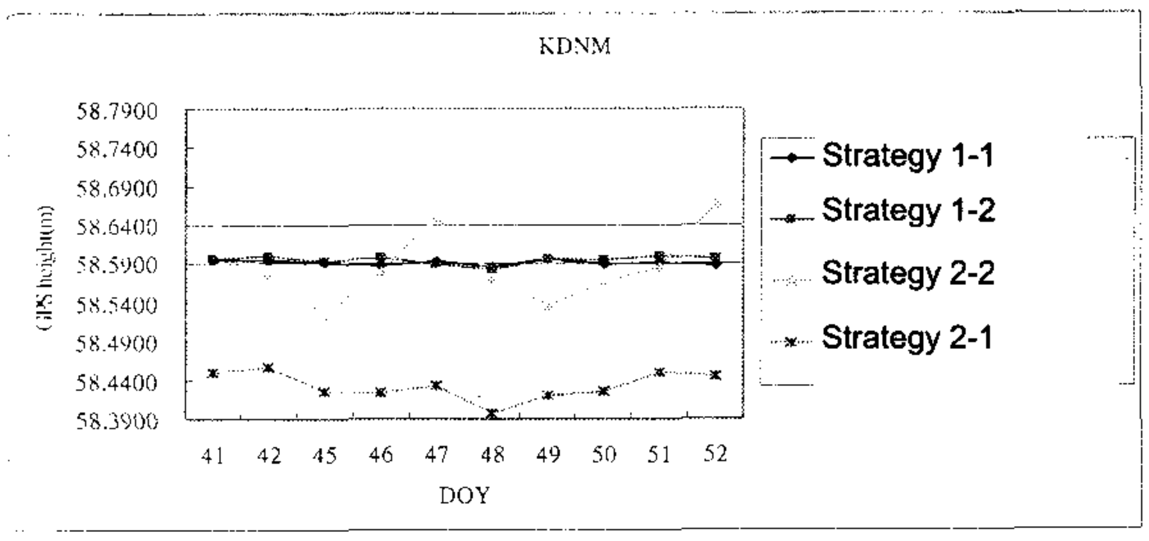

Figure 4. The GPS height of the KDNM station.

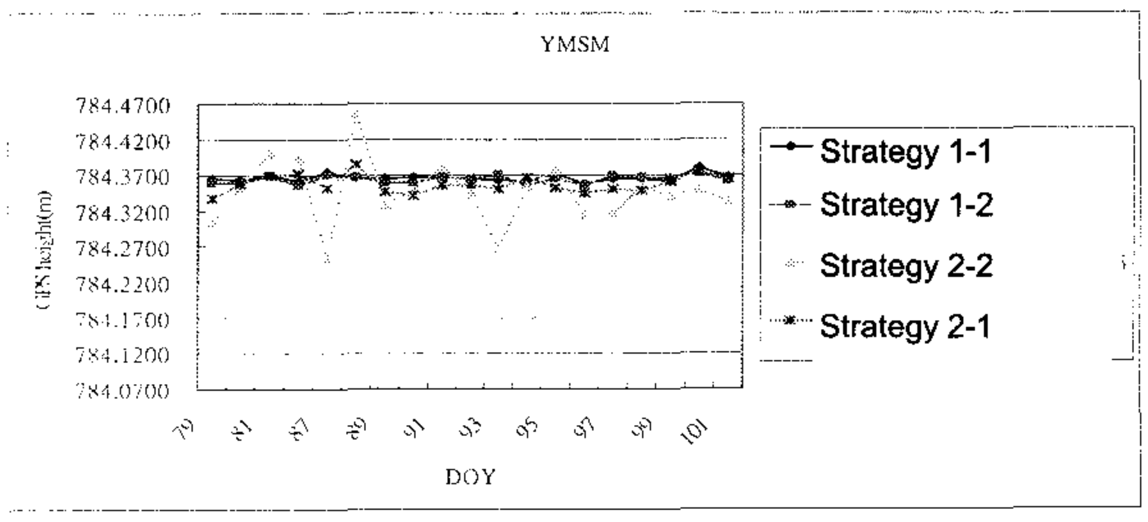

Figure 5. The GPS height of the YMSM station.

Table 1. The comparison of GPS height with different total delay corrections.

GPS station	Strategy 1-1 (1)		Strategy 1-2 (2)	
	Average of the GPS height (m)	Std. (mm)	Average of the GPS height (m)	Std. (mm)
FLNM (118 km)	138.8122	4.9751	138.8119	6.0361
KDNM (187 km)	58.5908	3.6557	58.5946	5.2303
YMSM (217 km)	784.3661	4.8734	784.3638	5.1712
GPS station	Strategy 2-1 (3)		Strategy 2-2 (4)	
	Average of the GPS height (m)	Std. (mm)	Average of the GPS height (m)	Std. (mm)
FLNM (118 km)	138.7583	9.4250	138.7644	32.5429
KDNM (187 km)	58.4326	17.8798	58.5803	45.7643
YMSM (217 km)	784.3574	12.2607	784.3456	46.0835

Table 2. The difference of the GPS height.

GPS station	(1)-(2) (cm)	(2)-(2) (cm)
FLNM (118 km)	0.0300	N/A
KDNM (187 km)	-0.3810	N/A
YMSM (217 km)	0.2332	N/A
GPS station	(3)-(2) (cm)	(4)-(2) (cm)
FLNM (118 km)	-5.3629	-4.7471
KDNM (187 km)	-16.2040	-1.4270
YMSM (217 km)	-0.6395	-1.8153

5. CONCLUSIONS

For the parameter estimation strategy, the lower the cut-off angel of the GPS observations is used in data processing, the better the repeatability of the GPS height can be obtained. Nevertheless, the difference between two different cut-off angels is within few mm.

For the external correction strategy, the GPS heights are lower than those from the parameter estimation strategy in most cases. When the surface meteorological measurements are incorporated in the data analysis, the average GPS heights show the same trend with the results from the WVR in spite of larger standard deviations.

In the KDNM GPS station, the measurements from the WVR are not precise enough to correct the real path delay because the observation site is surrounded by trees that cause noises to the measurements. The error is obvious in the results of the strategy 2-1, but there is no large effect for the horizontal coordinate estimation.

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