THE EFFECT OF SURFACE METEOROLOGICAL MEASUREMENTS ON PRECISION GPS HEIGHT DETERMINATION

Chuan-Sheng Wang
National Central University
Carlwang.cv87g@nctu.edu.tw

Yuei-An Liou
National Central University
yueian@csrsr.ncu.edu.tw

Cheng-Gi Wang
Ministry of Interior
wcg@gps.moi.gov.tw

ABSTRACT:

The positioning accuracy of the Global Positioning System (GPS) has been improved considerably during the past two decades. The main error sources such as ionospheric refraction, orbital uncertainty, antenna phase center variation, signal multipath, and tropospheric delay have been reduced substantially, if not eliminated. In this study, the GPS data collected by the GPS receivers that were established as continuously operating reference stations by International GNSS Service (IGS), Ministry of the Interior (MOI), Central Weather Bureau (CWB), and Industrial Technology Research Institute (ITRI) of Taiwan are utilized to investigate the impact of atmospheric water vapor on GPS positioning determination. The surface meteorological measurements that were concurrently acquired by instruments co-located with the GPS receivers include temperature, pressure and humidity data. To obtain the influence of the GPS height on the proposed impact study. A hydrodynamic ocean tide model (GOT00.2 model) and solid earth tide were used to improve the GPS height. The surface meteorological data (pressure, temperature and humidity) were introduced to the data processing with 24 troposphere parameters. The results from the studies associated with different GPS height were compared for the cases with and without *a* priori knowledge of surface meteorological measurements. The finding based on the measurements in 2003 is that the surface meteorological measurements have an impact on the GPS height. The associated daily maximum of the differences is 1.07 cm for the KDNM station. The impact is reduced due to smoothing when the average of the GPS height for the whole year is considered.

KEY WORDS: GPS, Tropospheric Path Delay

1. INTRODUCTION

The positioning accuracy of the Global Positioning System (GPS) has been improved considerably during the past two decades. Historically, the main error sources such as ionospheric refraction, orbital accuracy, antenna phase center variation, signal multipath, and tropospheric delay have been reduced substantially, if not eliminated. With the present state-of-the-art of GPS data analysis in geodesy, positioning accuracy is on the level of 1–2 mm in horizontal coordinates and 5–10 mm in the vertical coordinate [Bock and Doerflinger, 2000; Johansson et al., 1998; Liou et al., 2000]. There are two major reasons for the poor accuracy in the vertical axis. The first one is associated with a theoretical limit due to the satellite geometric distribution in the sky since observations are only used within a minimum elevation angle (typically about 15 °). The other one is due to tropospheric path delay, especially water vapor (or wet path delay) [Davis et al., 1985; Dodson et al., 1996; Emardson and Jarlemark, 1999; Liou et al., 2001].

In most GPS analysis procedures, the method of the double differenced was used to get the great reduction of 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 in GPS height determination with dual frequency GPS is path delay in the troposphere, especially due to the inhomogeneity and variability of water vapor. A 1-mm error in zenith tropospheric delay (ZTD) can produce biases in station height of 2-6 mm, for elevation cutoff angles between 5° and 25° [Santerre, 1991].

In general, the empirical meteorological models been used to predict path delay of the GPS signal with enough accuracy for most geodetic applications. However, for high precise applications, it is not sufficient to achieve the objective. There are two different strategies that have emerged for the goal, which are still in competition: parameter estimation and external correction. For the external correction, some special and expensive instruments must be applied. Because the cost of the equipment is much higher than that of a GPS receiver, only a few stations can set up the GPS receiver with the expansive equipment for external correction due to tropospheric effect at the same time. Normally, the parameter estimation becomes a popular method for correcting the path delay of the GPS signal in GPS analysis procedures.

The typical influence of troposphere on GPS height accuracy is shown in Table 1 [Rothacher et al., 1996], while its impact must be specially taken care of in the regions with highly variable and abundant of water vapor in the air, such as in the tropical and subtropical areas. The objective of the study is to analyze the effect of surface meteorological measurements nearby the GPS stations for GPS height determination.

Table 1 The order of magnitude for GPS height by the tropospheric influence. [Adopted from Rothacher et al., 1996]

T (° C)	P (mbar)	H (%)	$\left\lvert\frac{\partial\Delta\rho}{\Delta T}\right\rvert$ (mm/° C)	$\left\lvert\frac{\partial\Delta\rho}{\Delta P}\right\rvert$ (mm/ mbar)	$\left\lvert\frac{\partial\Delta\rho}{\Delta H}\right\rvert$ (mm/1%)
0°	1000	50	3	2	0.6
30°	1000	50	14	2	4
0°	1000	100	5	2	0.6
30°	1000	100	27	2	4

2. TROPOSPHERIC DELAY

When an electromagnetic wave propagates in the atmosphere, it is continuously refracted due to the varying index of refraction of the air along the ray path. There are two effects on a ray path: bending and retarding, which both produce an excess path length with respect to propagation in a 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, 1985]

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

where $N=(n-1)\times 10^6$ and n are the refractivity and index of refraction of the air, respectively, at a point s along the path. Refractivity of air is usually described by empirical formulas, e.g.,

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

where k_i are refractivity constants, ρ_d and ρ_v are densities (kg/m^3) of dry air and water vapor, respectively, R_d and R_v are specific gas constants for these constituents and T is atmospheric temperature (K).

In order not to use a ray-tracing method for the evaluation of equation (1), some assumptions are made to evaluate path delay. Especially, one assumes that path delay in an arbitrary direction is related to path delay at zenith, or zenith tropospheric delay (ZTD), by mapping functions [Davis, 1985]:

$$\Delta L = \Delta L_h^{\bar{z}} \times m_h(\varepsilon) + \Delta L_v^{\bar{z}} \times m_v(\varepsilon) \qquad (3)$$

where $\Delta L_h^{\bar{z}}$ and $\Delta L_v^{\bar{z}}$ are hydrostatic and wet delays at zenith, respectively, $m_h(\varepsilon)$ and $m_v(\varepsilon)$ are mapping functions and ε is the elevation angle. The hydrostatic term results from rewriting equation (2). Delays at zenith become:

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

$$\Delta L_v^{\bar{z}} = 10^{-6} k'_2 R_v \int \rho_v dz + 10^{-6} k_3 R_v \int \frac{\rho_v}{T} dz \qquad (5)$$

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

The zenith hydrostatic delay (ZHD), $\Delta L_h^{\bar{z}}$, is about 2.30 m, and represents 90–100 % of the zenith total delay (ZTD). The zenith wet delay (ZWD), ΔL_v, 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.

Hence, ZTD variations are significant, especially due to water vapor, and must be accurately monitored. The effect of a 1-mm error in ZTD will result mainly in a bias in the vertical co-ordinate of the GPS station of 2–6 mm, depending mainly on the elevation cut-off angle (5–25°) but also on site latitude [Santerre, 1991]. To achieve a 1-cm accuracy in relative heights from GPS measurements, ZTD must thus typically be corrected with an accuracy better than 3 mm (at 15° cut-off angle).

3. DATA COLLECTION AND COMPUTING METHOD

The GPS data were collected from GPS tracking Stations operated by the International GNSS Service (IGS) and Ministry of Interior (MOI), Central Weather Bureau (CWB), and Industrial Technology Research Institute (ITRI) of Taiwan. The total number of the GPS stations is 21.

The surveying time was 24 hours each day in 2003. For the GPS stations in Taiwan, permanent meteorological equipment was used for measuring the surface pressure, temperature and relative humidity.

In the GPS height determination, we used the final precise ephemeris (SP3 file) from the IGS and information of the phase center of antenna from U.S. National Geodetic Survey (NGS). Accroding to Beutler et al. [2001], the effect of solid earth tide and ocean tide are the order of few centimeters. In the current study, both of the tides have been considered. For solid earth tide, we used the function that has been announced by IERS in 1996 [McCarthy, 1996]. For ocean tide, the data of the GOT00.2 model [Scherneck, 1991] were introduced. They were computed from the web site of the Center for Astrophysics and Space Science in Sweden [http://www.oso.chalmers.se/~loading/].

Analysis is performed for all baselines with and without additional surface meteorological data. For all procedures, the parameter estimation method was used and 24 parameters were applied in each session. The Bernese software V4.2 developed by the Institute of Astronomy University of Berne was 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) were fixed.

4. RESULTS

In the most GPS data procedures, usually, the standard atmospheric situation (e.g. 1013.15 hPa for mean sea level pressure, converted to pressure at the height of the station with a standard temperature profile) is introduced to empirical meteorological model to correct the tropospheric path delay. In the study, we use the surface meteorological measurements to replace the standard atmospheric situation, to represent the real atmospheric situation. That is, more correct path delay in troposphere is applied in the GPS data analysis. Fig. 1 shows the daily variations of the GPS height without and with surface meteorological measurements for the 12 GPS stations cases in Taiwan in 2003, respectively. Fig. 2 shows the differences of daily variations of the GPS height.

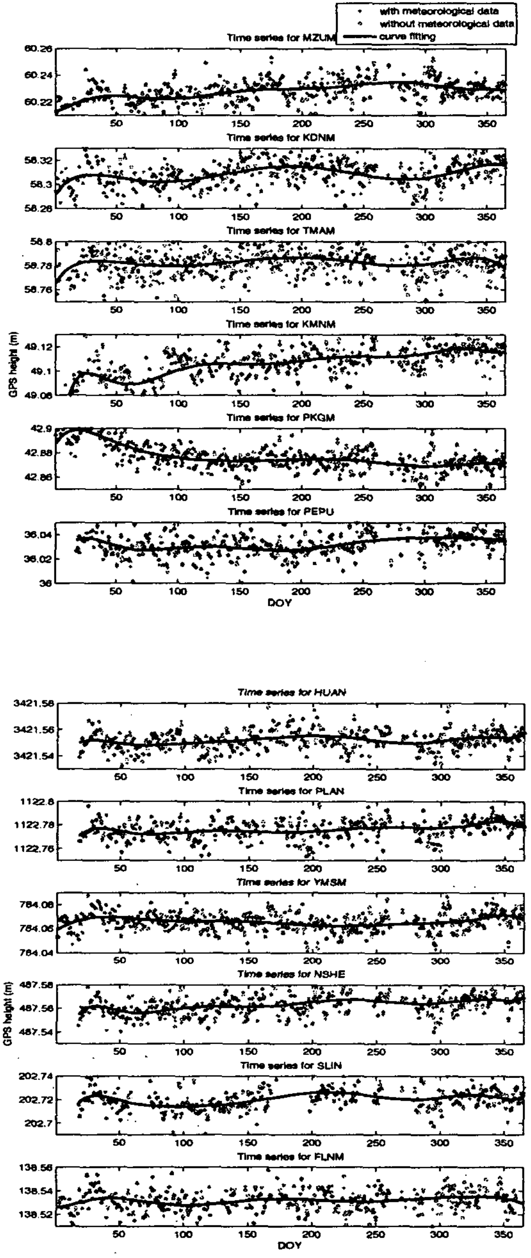

Figure 1 Variation of the daily GPS heights

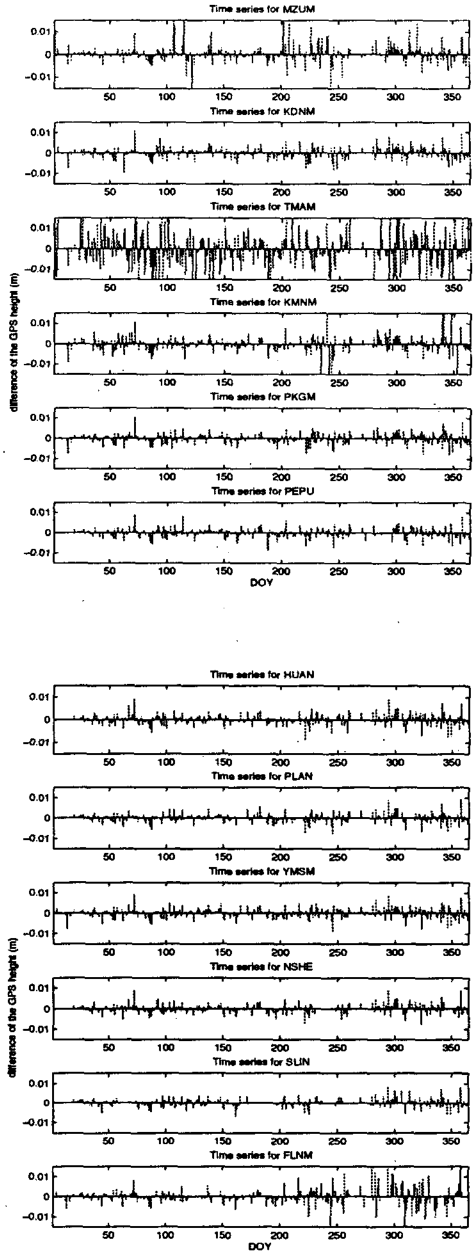

Figure 2 Variation of the difference of daily GPS heights

We observe the improvement in the GPS height determination when surface meteorological measurement is taken into account. The result is shown in Table 2. There is an important thing which must be carefully examined. When the surface meteorological data was used, if barometer can not work normally, the path delay will be correlated with the error due to pressure measurements. The influence of the error will be propagated into the GPS height position, like the FLNM, MZUM, KDNM and TMAM stations. The maximum difference of the GPS height without and with surface meteorological measurement can reach 1.07 cm. The variation of all value in the difference is between -1 cm and 1 cm. The effect of surface meteorological measurement on precision GPS height is about few mm order.

Table 2 The maximum and minimum difference of GPS height with and without surface meteorological measurements.

station name	HUAN	PLAN	YMSM	NSHE	SLIN	FLNM
maximum difference of the GPS height (m)	0.0090	0.0092	0.0094	0.0090	0.0088	0.0199
minimum difference of the GPS height (m)	-0.0091	-0.0074	-0.0087	-0.0076	-0.0069	-0.0159
station name	MZUM	KDNM	TMAM	KMNM	PKGM	PEPU
maximum difference of the GPS height (m)	0.0321	0.0107	0.0255	0.0811	0.0102	0.0089
minimum difference of the GPS height (m)	-0.0325	-0.0095	-0.0360	-0.1062	-0.0079	-0.0088

5. CONCLUSIONS

A hydrodynamic ocean tide model (GOT00.2 model) and solid earth tide were used to improve the GPS height. The surface meteorological data (pressure, temperature and humidity) were introduced to the data processing with 24 troposphere parameters. The results from the studies associated with different GPS height were compared for the cases with and without *a priori* knowledge of surface meteorological measurements. The finding based on the measurements in 2003 is that the surface meteorological measurements have an impact on the GPS height. The associated daily maximum of the differences is 1.07 cm for the KDNM station. For the other station, the variation of all value in the difference is between -1 cm and 1 cm.

One thing we can find in the result from static method is that the impact is reduced due to smoothing when the average of the GPS height for the whole year is considered.

According to empirical models, the sensitivity of zenith delay to surface pressure, temperature and relative humidity is about 2 mm/hPa, 5–20 mm/°C and 1–3 mm/%, respectively [Janes, 1991]. Though the mm-level accuracy in ZTD correction should be achievable with precise meteorological sensors, it is well known that surface measurements are often not representative of the vertical profiles through the whole troposphere. Hence, even the surface pressure, temperature and relative humidity are introduced into the data procedure, there is a theoretically limited in accuracy.

Acknowledgment

The authors thank the Ministry of Interior (MOI) of Taiwan for the support of this study.

References:

Bock, O., E. Doerflinger, 2000, “Atmospheric processing methods for high accuracy positioning with the Global Positioning System,” COST-716 Workshop, Soria Moria, Oslo (N), July 10-12, Laboratoire OEMI, IGN-SR 00-003/L-COM-OB.

Johansson, J.M., T. R. Emardson, P. O. J. Jarlemark, L. P. Gradinarsky, G. Elgered, 1998, “The atmospheric influence on the results from the Swedish GPS network,” *Phys. Chem. Earth*, 23, 107–112.

Liou, Y. A., C. Y. Huang, Y. T. Teng, 2000, “Precipitable water observed by ground-based GPS receivers and microwave radiometry,” *Earth, Planets, and Space*, 52(6), 445-450.

Davis, J., T. Herring, I. Shapiro, A. Rogers and G. Elgered, 1985, “Geodesy by radio-interferometry: effects of atmospheric modeling errors on estimates of baseline lengths,” *Radio Sci.*, 20, 1593-1607.

Dodson, A. H., P. J. Shardlow., L. C. M. Hubbard, G. Elegered, P. O. J. Jarlemark, 1996, “Wet tropospheric effects on precise relative GPS height determination,” *J. Geod.*, 70, 188–202.

Emardson, T. R., P. O. J. Jarlemark, 1999, “Atmospheric modelling in GPS analysis and its effect on the estimated geodetic parameters,” *J. Geod.*, 73, 322–331.

Liou, Y. A., Y. T. Teng, T. Van Hove, and J. Liljegren, 2001, “Comparison of precipitable water observations in the near tropics by GPS, microwave radiometer, and radiosondes, ” *J. Appl. Meteor*, 40(1), 5-15.

Santerre, R., "Impact of GPS satellite sky distribution," Manuscr. Geod. Vol. 16, 28–53, 1991.

Rothacher, M., L. Mervart, G. Beutler, E. Brockmann, S. Fankhauser, W. Gurtner, J. Johnson, S. Schaer, T. Springer, R. Weber, 1996, “*The Bernese GPS Software Version 4.0*,” Astronomical Institute, University of Berne.

Ichikawa, R., "Estimation of atmospheric excess path delay based on three-dimensional numerical prediction model data," *J. Geod. Soc.* Japan, 41, 379-408, 1995.

Elgered, G., "*Tropospheric radio path delay from ground-based microwave radiometry*" in Atmospheric remote sensing by microwave radiometry, chap. 5, M.A. Janssen (ed), Wiley, New-York, 1993.

Santerre, R., "Impact of GPS satellite sky distribution," *Manuscr. Geod.* Vol. 16, 28–53, 1991.

Beutler, G. E. Brockmann, R. Dach, P. Fridez, W. Gurtner, U. Hugentobler, J. Johnson, L. Mervart, M. Rothacher, S. Schaer, T. Springer, and R. Weber, 2001, “*Bernese GPS Software Version 4.2*,” Astronomical Institute, University of Berne

Scherneck, H.-G. , 1991, A parametrized solid earth tide model and ocean tide loading effects for global geodetic baseline measurements, *Geophys. J. Int.*, 106, pp. 677–694.

McCarthy, D.D., 1996, IERS Conventions, IERS Technical Note 21, Observatoire de Paris, Paris

Janes, H.W., R.B. Langley, S.P. Newby, 1991, “Analysis of tropospheric delay prediction models: comparisons with ray-tracing and implications for GPS relative positioning”, *Bulletin Géodésique*, 65, pp. 151–161