THE EFFECT OF SURFACE METEOROLOGICAL MEASUREMENTS ON GPS HEIGHT DETERMINATION

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ABSTRACT ... Positioning accuracy by the Global Positioning System (GPS) is of great concern in a variety of research tasks. It is limited due to error sources such as ionospheric effect, orbital uncertainty, antenna phase center variation, signal multipath, and tropospheric influence. In this study, the tropospheric influence, primarily due to water vapour inhomogeneity, on GPS positioning height is investigated. The data collected by the GPS receivers along with co-located surface meteorological instruments in 2003 are utilized. The GPS receivers are established as continuously operating reference stations by the Ministry of the Interior (MOI), Central Weather Bureau (CWB), and Industrial Technology Research Institute (ITRI) of Taiwan, and International GNSS Service (IGS). The total number of GPS receivers is 21. The surface meteorological measurements include temperature, pressure, and humidity. They are introduced to GPS data processing with 24 troposphere parameters for the station heights, which are compared with those obtained without *a priori* knowledge of surface meteorological measurements. The results suggest that surface meteorological measurements have an expected impact on the GPS height. The daily correction maximum with the meteorological effect may be as large as 9.3 mm for the cases of concern.

KEY WORDS: GPS, Tropospheric Path 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 vertical coordinate [Bock and Doerflinger, 2000; Johansson et al., 1998; Liou et al., 2000]. There are two major reasons for the less accuracy in 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 used 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 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.meeting organisers in digital form. However, if in exceptional circumstances, the paper cannot be prepared digitally, it must be prepared on A4 paper according to these guidelines, and sent to the organisers for scanning.

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. A 1-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].

Several empirical meteorological models have been developed to estimate tropospheric path delay for some geodetic applications. Nevertheless, they do not provide adequate accuracy in vertical coordinate and become a challenging problem for geodesists to conquer in order to fully utilize the advantages of continuous GPS networks. Two different strategies that have emerged to resolve the troposhperic effect are still in competition: the parameter estimation approach and the external correction approach [Bock and Doerflinger, 2000]. For the external correction approach, some special and expensive instruments such as water vapour radiometer can be applied. Because the cost of the equipments is much higher than that of a GPS receiver, only a few GPS stations are equipped with the radiometers for implementing external corrections. That is, the parameter estimation approach is generally adopted in the GPS data analysis procedures. In this study, we apply the parameter estimation approach to study the effect of surface meteorological measurements on the GPS height determination.

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 kinds of effects on a ray path: bending and retarding. Both of them 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 at a point s along the path, respectively. Refractivity of air is usually described by the empirical formula (e.g. 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 are refractivity constants, ρ_d is the density of dry air, ρ_w is 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, 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 equation (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 near 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 COMPUTING METHOD

The GPS data with surveying time 24 hours a day were collected from GPS tracking Stations operated by the Ministry of Interior (MOI), Central Weather Bureau (CWB), and Industrial Technology Research Institute (ITRI) of Taiwan, and the International GNSS Service (IGS) in 2003. The total number of the GPS stations is 21.

In the GPS height determination, we use the final precise ephemeris (SP3 file) from the IGS and phase center of antenna provided by U.S. National Geodetic Survey (NGS). According to Beutler et al. [2001], the effects of solid earth tide and ocean tide are on the order of a few centimeters. In this study, both types of tides 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/].

Analysis is performed for all baselines without and with additional surface meteorological data. For all procedures, the atmospheric parameter estimation method is used and 24 parameters are applied in each session. The Bernese software V4.2 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.

4. RESULTS

Table 1 lists the GPS heights and standard deviations of daily solutions without incorporating the surface meteorological data into GPS data processing. Among the stations of concern, the highest and lowest GPS stations are HUAN and TNSM with heights of 3421 and 18 m, respectively. Generally, the higher the station is the smaller the height variation is. For example, the standard deviations of GPS heights for HUAN and TNSM are about 7.8 and 12.6 mm, respectively. This indicates that water vapor may enlarge the uncertainty in GPS height determination. That is, the variability of GPS height scales with the total water vapor burden.

Table 1. GPS heights and standard deviations of daily solutions.

	HUAN	PLAN	YMSM	NSHE	SLIN	FLNM
GPS height (m)	3421	1122	784	487	202	138
Std. Dev. (mm)	7.8	9.0	7.9	8.9	10.1	9.3
	MZUM	KDNM	TMAM	PKGM	PEPU	TNSM
GPS height (m)	60	58	58	42	36	18
Std. Dev. (mm)	8.8	11.2	10.3	11.4	10.0	12.6

Figures 1-4 show correlations between GPS heights and surface meteorological measurements of pressure, temperature, relative humidity, and rainfall, respectively The corresponding correlation coefficients are low with values of -0.18, -0.26, 0.35, and 0.43, respectively. It is clear that any individual correlation is not high, while each individual surface parameter has some influence on the height determination. This is the reason why an integrated effect of all the surface meteorological measurements on the GP height determination is critical and must be removed as much as possible.

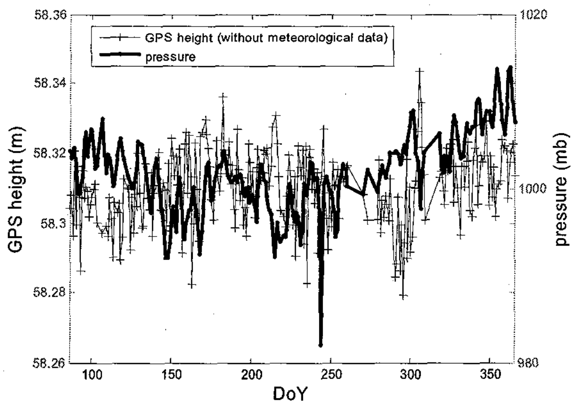

Figure 1. Daily KDNM GPS height and pressure.

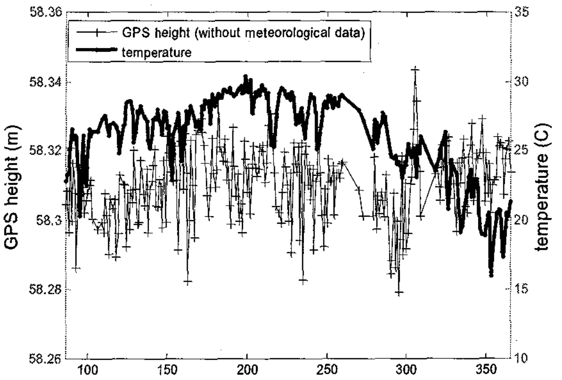

Figure 2. Daily KDNM GPS height and temperature.

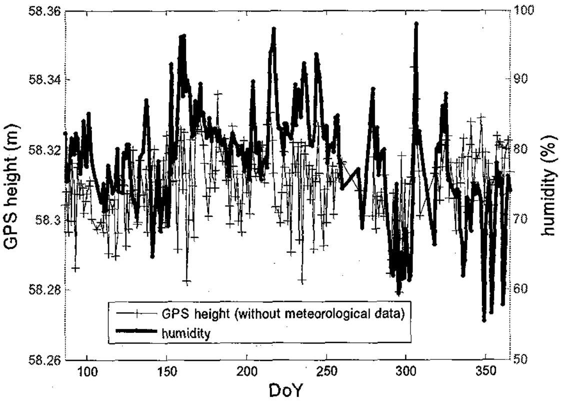

Figure 3. Daily KDNM GPS height and humidity.

In most GPS data procedures, the standard atmospheric model (e.g. 1013.15 hPa at mean sea level pressure, used to derive the pressure at the station height with a standard atmosphere) that is characterized by empirical meteorological models is introduced to correct tropospheric path delay. For comparison, we also incorporate surface meteorological measurements into GPS data analysis to take into account the tropospheric effects. Essentially, more correct path delay in troposphere is then applied. **Fig. 5** shows the daily variations of GPS height without and with surface meteorological measurements for the KDNM station. **Fig. 6** shows the corresponding differences in the daily heights given in **Figure 5**. The maximum and minimum differences of the KDNM GPS heights are 9.3 and -8.3 mm, respectively. Results indicate that the correction in GPS height with meteorological measurements may reach as high as 9.3 mm. Results for the other stations are not shown in figures, but quantitatively summarized in **Table 2**.

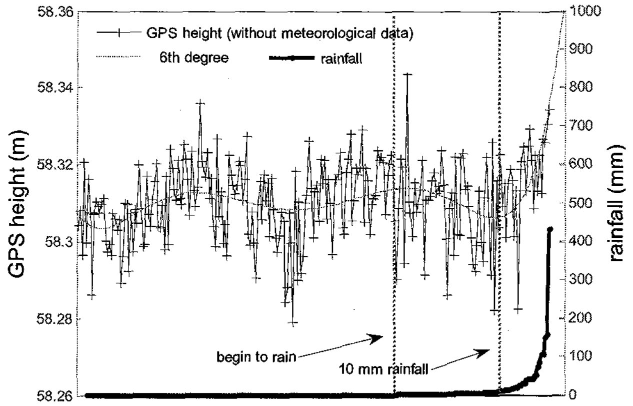

Figure 4. Daily KDNM GPS height and rainfall.

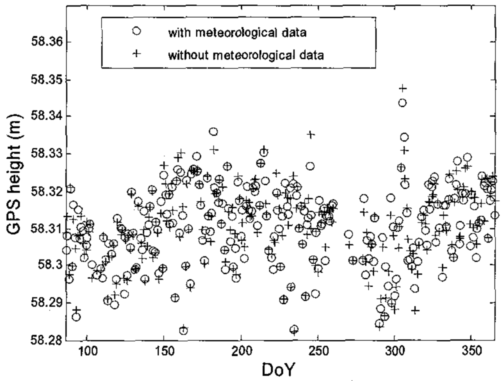

Figure 5. Daily KDNM GPS heights.

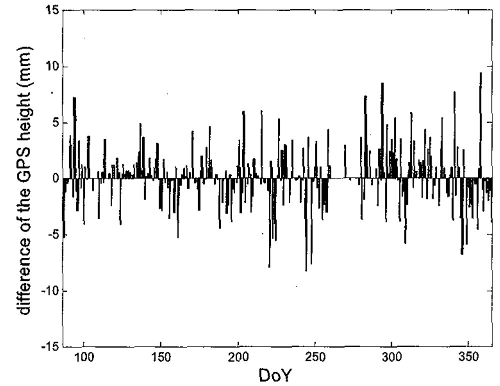

Figure 6. Corresponding differences in the daily KDNM GPS heights given in Figure 1.

The maximum and minimum differences in GPS height with and without surface meteorological measurements are given in **Table 2**. Generally speaking, they vary between -10 and 10 mm except for those cases highlighted. The effect of surface meteorological measurement on GPS height is on the order of few mm based on daily observation. We suspect that larger variations for the highlighted cases of FLNM, MZUM, TMAM and KMNM stations may be associated with higher variable barometric measurements. Note that path delay is very much correlated with surface pressure whose absolute influence is relatively large compared to temperature and relative humidity. Error from the barometric measurements may be propagated into GPS height determination. Quality of surface pressure measurements shall be very carefully controlled.

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

station **difference in GPS height, mm**	HUAN	PLAN	YMSM	NSHE	SLIN	FLNM
Maximum	9.0	9.2	9.4	9.0	8.8	19.9
Minimum	-9.1	-7.4	-8.7	-7.6	-6.9	-15.9
station difference in GPS height, mm	MZUM	KDNM	TMAM	KMNM	PKGM	PEPU
maximum	32.1	9.3	25.5	81.1	10.2	8.9
minimum	-32.5	-8.3	-36.0	-106.2	-7.9	-8.8

5. CONCLUSIONS

A hydrodynamic ocean tide (GOT00.2) model and a solid earth tide model are used to reduce both tides' influence on GPS height. The surface meteorological data (pressure, temperature, and relative humidity) are then introduced to GPS data processing with 24 troposphere parameters. The results of GPS heights without and with and *a priori* knowledge of surface meteorological measurements are analyzed and compared. Based on the measurements in 2003, it is found that the surface meteorological measurements have an impact on GPS height determination with a daily maximum influence of 0.93 cm for the KDNM station. For the other station, the influence generally ranges between -1 cm and 1 cm. Furthermore, the results show that generally the higher the GPS stations are the smaller the standard deviations on the height determination are. It indicates that the variability of GPS height scales with the total water vapor burden.

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