GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L23809, doi:10.1029/2008GL035929, 2008

Impact of surface meteorological measurements on GPS height determination

Chuan-Sheng Wang,[1] Yuei-An Liou,[2] and Ta-Kang Yeh[3]

Received 8 September 2008; revised 20 October 2008; accepted 21 October 2008; published 6 December 2008.

[1] Although the topic of the positioning precision of the Global Positioning System (GPS) has been studied extensively, it focuses mostly on the error sources such as the ionospheric effect, antenna phase center variation and tropospheric influence. This investigation addresses the influence of the tropospheric effect on the results of the height determination. Used data are obtained from GPS receivers of a network and co-located surface meteorological instruments in 2003. Two approaches, parameter estimation and external correction, are utilized to correct the zenith tropospheric delay (ZTD) by applying the surface meteorological measurements (SMM) data. The GPS height can be affected by an incorrect pressure measurement up to a few meters, and the root-mean-square (RMS) of the daily solution can range from millimeters to a few centimeters, no matter which approach is adopted. The effect is less significant when using SMM for parameter estimation, but the trend of corrections on the GPS height is more consistent at either higher or lower altitudes. By external correction using SMM and Saastamoinen model, the GPS height reaches a few centimeters repeatability, while the RMS of the daily solution displays an improvement of about 2–3 mm.

Citation: Wang, C.-S., Y.-A. Liou, and T.-K. Yeh (2008), Impact of surface meteorological measurements on GPS height determination, *Geophys. Res. Lett.*, *35*, L23809, doi:10.1029/2008GL035929.

1. Introduction

[2] Space-based geodetic systems, especially the Global Positioning System (GPS), have been widely utilized in recent decades. For example, the GPS technology has been applied to the fields of Plate Boundary Observatory (PBO), crust deformation and land survey [*Yeh et al.*, 2006]. Since the positioning precision 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 precision 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].

[3] Most GPS data analysis procedures utilize double differencing to eliminate the clock error. Carrier phase ambiguities and cycle slips can be repaired or estimated with new ambiguity. Carrier phase ambiguities can be eliminated by code date processing or triple differencing, while ionospheric delay can be corrected by modeling or eliminated by dual frequency combinations [*Xu*, 2007]. However, the dual-frequency GPS scheme still suffers from path delay of the troposphere associated with inhomogeneity and variability of water vapor. A 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].

[4] Two different tactics, parameter estimation and external correction, are undertook to resolve the tropospheric 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*, 2006] 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. Tropospheric Path Delay

[5] An electromagnetic wave propagating through the atmosphere is continuously refracted due to the varying index of refraction of the air along the ray path. A ray path can either bend or retard, both of which generate an excess path length with respect to the propagation in vacuum. The excess path length from bending is generally about 1 cm at 15°, which is usually negligible [*Ichikawa*, 1995]. Excess path length as the result of 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 $N = (n - 1) \times 10^6$ and n indicates the refractivity and index of refraction of the air at a point S along the ray path, respectively.

[6] Certain assumptions are usually made when deriving the path delay. For instance, the path delay in an arbitrary

---

[1] Center for Space and Remote Sensing Research and Institute of Space Sciences, National Central University, Jhongli, Taiwan.

[2] Center for Space and Remote Sensing Research, National Central University, Jhongli, Taiwan.

[3] Institute of Geomatics and Disaster Prevention Technology, Ching Yun University, Jhongli, Taiwan.

Copyright 2008 by the American Geophysical Union.
0094-8276/08/2008GL035929$05.00

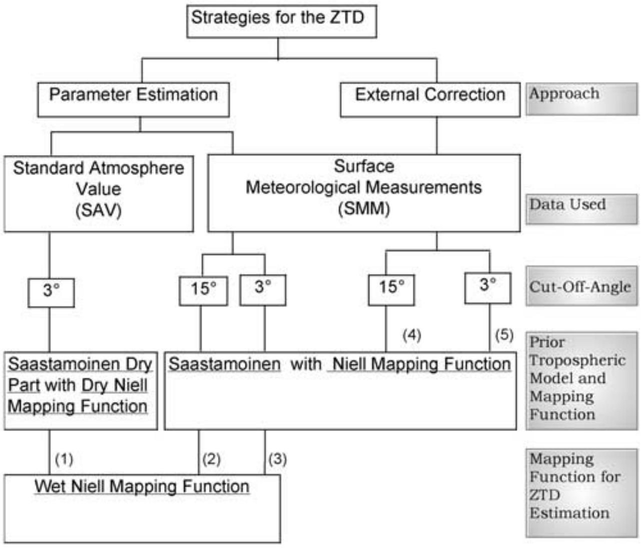

Figure 1. The structure of the strategies for the ZTD.

direction is assumed to be related to the path delay at the zenith or ZTD by mapping functions [*Davis et al.*, 1985] (or tropospheric obliquity factor)

$$\Delta L = \Delta L_h^z \times m_h(\varepsilon) + \Delta L_w^z \times m_w(\varepsilon) \quad (2)$$

where ΔL_h^z and ΔL_w^z indicate the hydrostatic and wet delays at the zenith, respectively; $m_h(\varepsilon)$ and $m_w(\varepsilon)$ are mapping functions, and ε is the elevation angle.

[7] The zenith hydrostatic delay (ZHD) ΔL_h^z is approximately 2.30–2.60 m at sea level, and represents 90–100 % of the ZTD. The ZWD ΔL_w varies roughly as 0–40 cm between the poles and the equator, and from few cm to about 20 cm during the year at mid-latitudes. The variation in ZTD must be accurately and carefully monitored. The effect of a 1 mm error in ZTD results in a bias of nearly 2.6–6.5 mm in GPS station height, depending mainly on the elevation cutoff angle (5°–25°) and the site latitude [*Santerre*, 1991].

3. Data Collection

[8] The GPS data with a daily survey time of 24 hours were obtained from 5 GPS tracking stations operated by the Ministry of the Interior (MOI) in Taiwan 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). A done by *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.

4. Methodology

[9] 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).

[10] 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 Figure 1. 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* model depending on

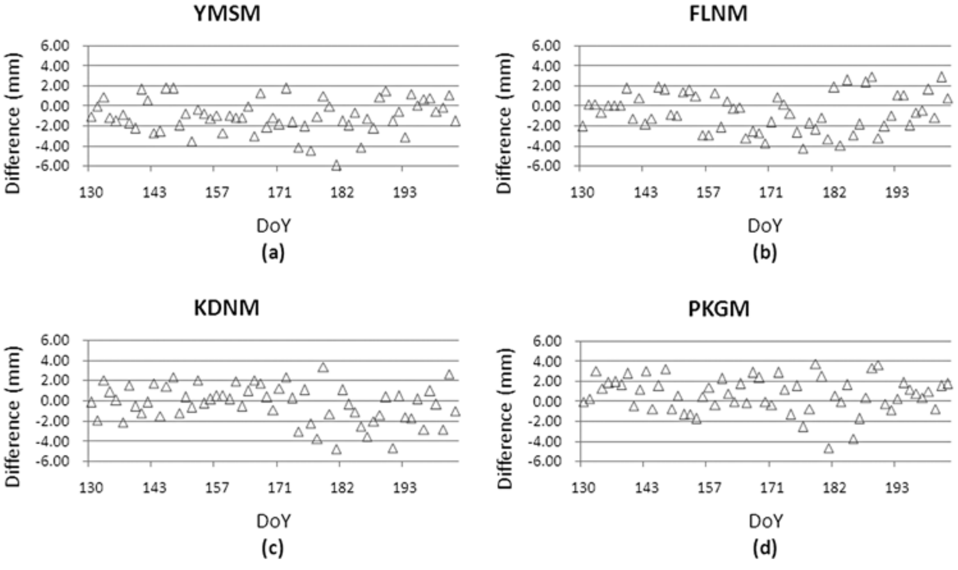

Figure 2. The difference of the GPS heights (result (1) minus result (3)) between the SMM data with or without *a priori* ZTD in parameter estimation approach.

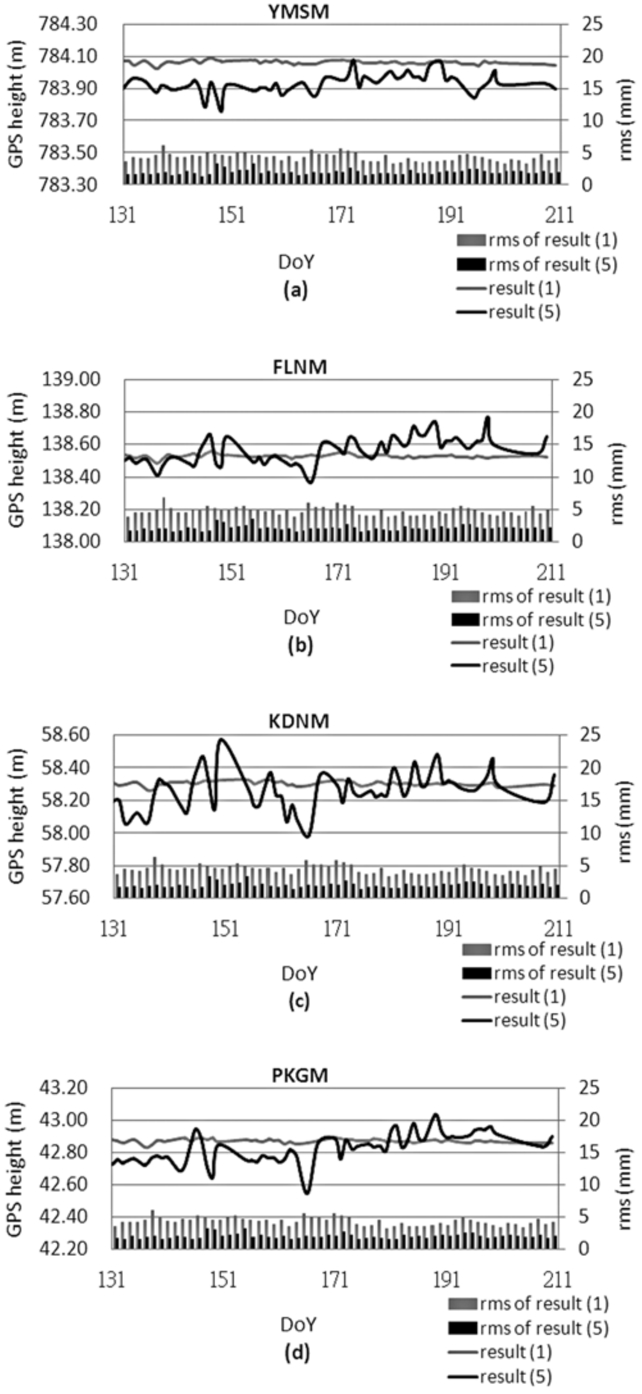

Figure 3. The comparison (result (1) and result (5)) of the GPS height and the RMS of the daily solution by external correction approach.

height follows *Berg* [1948]. The other data set is gained from data observed at the GPS receiver sites.

[11] 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. The Niell Mapping Function is recommended from the Bernese software manual, but, at least, there three other kinds of newer mapping functions (site dependent Vienna Mapping Functions 1 (VMF1), grid VMF1 and Global Mapping Functions) that can be applied for comparison in the future [*Boehm et al.*, 2006; *Kouba*, 2007].

5. Results

[12] 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* ZTD 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 ZTD different. The trends in Figure 2 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 both solutions. Because the SMM data cannot represent the entire tropospheric profile, the different data sets in the parameter estimation approach makes only few millimeters difference in GPS heights and few sub-millimeters difference in RMS of daily solutions.

[13] 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 negative differences values in Figure 2 are 69.5%, 57.6%, 50.9% and 30.5%, respectively. The amount of the negative difference increased with the GPS height. 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

Table 1. 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
		Standard Deviation (mm)		
Result (1)	11.2	11.5	12.7	10.7
Result (5)	57.5	80.8	111.4	92.6

Table 2. 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 Degrees) Minus (Result (3), 3 Degrees) (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 Degrees) Minus (Result (5), 3 Degrees) (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

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* ZTD derived from the SMM data are closer to the true atmospheric situation than the SAV. This indicates that the water vapor plays an important role to reduce the effect of atmosphere on GPS height. Consequently, the positive correction at higher station (YMSM) and negative correction at lower station (PKGM) can be obtained as shown in Figure 2, while the trend of corrections on the GPS height is more consistent at either higher or lower altitudes.

[14] 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. Figure 3 displays the GPS height and RMS of daily solution obtained from both approaches. Figure 3 demonstrates that the repeatability of the GPS height is inadequate when using the SMM data. 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 phenomenon could be a consequence of the reduced number of unknowns in the observation equations.

[15] "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.* [1990]. This observation is consistent with the results in Table 1. The standard deviation (Std. Dev.) of the GPS heights during the observing time shows that the SMM data (without tropospheric estimation from the measurements) make the outcome unstable, as occurred in the results. A GPS station at a higher altitude is less affected by the water vapor. The ZTD, which is corrected from the Saastamoinen model, and after estimation from measurements, 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 steadiest, as indicated in Figure 3.

[16] 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 15° to 3°.

[17] 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 average of the differences in Table 2 is about ±1mm and the standard deviation is about 2–3 mm 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 and the standard deviation is about 4 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.

[18] The use of SMM data presents one important issue. If the error in the pressure measurement is found in the daily meteorological measurement file, it significantly and adversely affects the precision. Several epochs show incorrect measurements in the daily file. The imprecision 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.

6. Conclusions

[19] 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.

[20] 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 either higher or lower altitudes, due to precise surface meteorological measurement.

[21] 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.

[22] The cut-off-angle does not affect the precision of the GPS height. The experimental results obtained by using the Niell mapping function on SMM data are stable.

[23] Incorrect pressure measurements lead to poor precision. The imprecision of the GPS height can reach several meters whereas the RMS of the daily solution ranges from a few millimeters to centimeters, no matter which approach is used.

[24] Analytical results show that higher GPS stations generally have better repeatability for height determination. Thus, the variability of GPS height increases with the total water vapor burden [*Liou et al.*, 2001]. In the future, data from high altitude GPS stations processed will be applied with SMM data to investigate this phenomenon properly.

[25] **Acknowledgments.** 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).

References

Berg, H. (1948), *Allgemeine Meteorologie*, Dümmlers, Bonn, Germany.

Beutler, G., W. Gurtner, M. Rothacher, U. Wild, and E. Frei (1990), Relative static positioning with the Global Positioning System: Basic technical considerations, in *Global Positioning System: An Overview, Int. Assoc. Geod. Symp.*, vol. 102, edited by Y. Bock and N. Leppard, pp. 1–23, Springer, New York.

Bock, O., and E. Doerflinger (2000), Atmospheric processing methods for high accuracy positioning with the Global Positioning System, paper presented at the COST Action 716 Workshop, Eur. Coop. Field Sci. Tech. Res., Oslo, 10–12 July.

Boehm, J., B. Werl, and H. Schuh (2006), Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data, *J. Geophys. Res.*, *111*, B02406, doi:10.1029/2005JB003629.

Davis, J. L., T. A. Herring, I. I. Shapiro, A. E. E. Rogers, and G. Elgered (1985), Geodesy by radio interferometry: Effects of atmospheric modeling errors on estimates of baseline length, *Radio Sci.*, *20*, 1593–1607.

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

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

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

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

Kouba, J. (2007), Implementation and testing of the gridded Vienna Mapping Function 1 (VMF1), *J. Geod.*, *82*, 193–205, doi:10.1007/s00190-007-0170-0.

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. Meteorol.*, *40*(1), 5–15.

McCarthy, D. D. (1996), IERS Conventions, *IERS Tech. Note 21*, Obs. de Paris, Paris.

Niell, A. E. (1996), Global mapping functions for the atmosphere delay at radio wavelengths, *J. Geophys. Res.*, *101*, 3227–3246.

Rothacher, M., and G. Beutler (1998), The role of GPS in the study of global change, *Phys. Chem. Earth*, *23*(9–10), 1029–1040.

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

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

Tregoning, P., and T. A. Herring (2006), Impact of a priori zenith hydrostatic delay errors on GPS estimates of station heights and zenith total delays, *Geophys. Res. Lett.*, *33*, L23303, doi:10.1029/2006GL027706.

Xu, G. (2007), *GPS: Theory, Algorithms, and Applications*, 2nd ed., Springer, Berlin.

Yeh, T. K., C. S. Wang, C. W. Lee, and Y. A. Liou (2006), Construction and uncertainty evaluation of a calibration system for GPS recievers, *Metrologia*, *43*(5), 451–460, doi:10.1088/0026-1394/43/5/017.

Y.-A. Liou and C.-S. Wang, Center for Space and Remote Sensing Research, National Central University, Jhongli 320 Taoyuan, Taiwan. (yueian@csrsr.ncu.edu.tw)

T.-K. Yeh, Institute of Geomatics and Disaster Prevention Technology, Ching Yun University, Jhongli 320 Taoyuan, Taiwan.