GEOPHYSICAL EFFECTS ON SITE DISPLACEMENTS FOR PERMANENT GPS TRACKING STATIONS IN TAIWAN

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ABSTRACT

High precision GPS measurements are required for many scientific applications, such as the establishment of national fundamental networks, the monitoring of crustal deformation, and the determination of sea level changes. It is of importance to develop the proper strategies and techniques for GPS observation and data processing to effectively enhance the accuracy of coordinates based on GPS measurements. One of the GPS error sources, based on the geophysical effects, can theoretically cause significant site displacements during the GPS observation. The geophysical effects have to be investigated if a higher level of GPS positioning accuracy is expected. It can be achieved through the use of a number of models defined for the corrections of such geophysical effects. The site displacements caused by the geophysical effects, in terms of the polar tides and atmospheric pressure loading, have been practically estimated from models to realise their influence on high accuracy GPS positioning. The models have been detailed and the effects have been estimated using published IERS data, and meteorological data observed close to GPS tracking stations in Taiwan. These stations have played a core role on the latest realization of a geocentric reference system in this area.

1. INTRODUCTION

In order to determine the highest accuracy of GPS coordinates for the increasing growth of requirement, it is important to investigate and improve any error models used in the data processing. Many limiting factors on the accuracy of GPS positioning, such as the errors related to the satellite orbit, atmospheric propagation, site environment, and natural effects, are all required to be modelled and evaluated.

The so-called natural effects are one of the systematic errors related to the geophysical effects, mainly the earth body tides, ocean tide loading, polar tides, and atmospheric pressure loading. The tides give periodic loads on the earth's surface which cause a certain kind of site displacement. In actual fact, it is common to ignore the geophysical effects in most commercial GPS processing software. However, this ignorance may not be an adequate approach when millimetric accuracies are required for some of the GPS applications. Hence, the corrections made for the site displacements are required if the highest accuracy of coordinate is expected to be determined by using GPS technique.

The tidal deformation of the earth, resulting from the tidal forces of the moon and sun, has been shown to introduce associated horizontal and vertical displacements of the order of 40 cm over 6 hours [Baker, 1984]. Once the body tide Love numbers are known and the coordinates of a site plus the lunar and solar ephemerides are given, the short-period horizontal and vertical earth body tide deformations can be computed and corrected in the GPS processing procedure for any epoch to an accuracy of about 2 mm [Baker et al., 1995].

In addition to earth body tides, the ocean tides also give periodic variations of surface mass loading on the earth's surface, which cause further tidal deformation of over 10 cm in some areas [Baker et al., 1995]. If an ocean tide model is given with an elastic earth model, the ocean tide loading deformation of the earth can be calculated. Its influence on GPS baseline precision has been found by the RMS scatter whose values can be reduced by around 15-20 mm, when ocean tide loading model was applied [Chang, 1995]. The two relatively large displacements caused by the earth body tides and ocean tide loading are of increasing importance in high precision GPS measurements made on the surface of the earth.

Another tide-related deformation is the polar tides, which represent the elastic response of the earth to changes in spin axis orientation. Its maximum uplift is only a few percent of the earth tide displacements, but it leads to changes in station position of up to 15 mm [Gipson and Ma, 1998]. Moreover, the interaction between the atmosphere and the earth is through pressure loading at the earth's surface and through the gravitational attraction of the atmospheric mass. A time-varying atmospheric pressure mass can, thus, lead to vertical displacements of several millimetres [Blewitt et al., 1994]. These two kinds of deformation, namely the polar tides and atmospheric pressure loading, regarded as part of the geophysical effects on GPS are mainly discussed in this paper.

The geophysical effects have been conventionally investigated for VLBI, one of the large scale of space geodetic techniques. As GPS has been widely used for the applications based on different scales of range, the models which can be properly applied to the corrections for site displacements are consequently required [Poutanen et al., 1996]. This paper aims at realising and investigating the currently available models, particularly the models used to estimate the site displacements caused by the polar tides and atmospheric pressure loading. The tests are presented based on the estimation of site displacements, acting to the GPS tracking stations in Taiwan, from the models used.

2. ESTIMATION MODELS

The error sources applied to the GPS data processing are taken into account mainly based on the scale of the GPS network, the period of the observation session, and the accuracy of the positioning solution. One of the error sources, namely the site displacements related to the geophysical effects, is proposed to investigate its cause, period, and influence to the GPS positioning. Therefore, the models used and data required both need to be defined for the estimation of site displacements caused by the effects of polar tides and atmospheric pressure loading.

The models proposed are based on those carried out by the International Earth Rotation Service (IERS) [McCarthy, 1996]. This is because the most important reference frame for geodetic applications is that maintained by the IERS, the so-called IERS Terrestrial Reference Frame (ITRF) [Boucher et al., 1998]. The ITRF is realised through a list of coordinates of terrestrial stations and their velocity fields, which are well-determined by the most precise space geodetic techniques. For high accuracy GPS, the station coordinates with centimetre-level accuracy, based on the ITRF, are normally required to be provided. The site displacements caused by the geophysical effects are, hence, of importance to be estimated and corrected during the data processing.

2.1 Polar Tides

The variations of GPS-based coordinates caused by the rotational deformation due to polar motion have been recommended to be taken into account for high accuracy GPS by the IERS [McCarthy, 1996]. The basic consideration is that the perturbation in the centrifugal potential is related to the Earth‘s rotation. When (x, y, z) is chosen as a terrestrial system of reference, a first order perturbation of the centrifugal potential (ΔV) can be expressed by

$$\Delta V(r,\theta,\lambda) = -\frac{\Omega^2 r^2}{2}\sin 2\phi\left(m_1 \cos\lambda + m_2 \sin\lambda\right) \tag{1}$$

as

$$V = \frac{1}{2}\left[r^2\left|\bar{\Omega}\right|^2 - \left(\bar{r}.\bar{\Omega}\right)^2\right] \tag{2}$$

and

$$\bar{\Omega} = \Omega\left(m_1\bar{x} + m_2\bar{y} + \left(1+m_3\right)\bar{z}\right) \tag{3}$$

in which, Ω is the mean angular velocity of Earth's rotation, m_1 and m_2 are small dimensionless parameters describing polar motion, m_3 is the variation in the rotation rate, which is neglected in equation (1) due to its small influence, and r is the radial distance to the GPS station.

The radial displacement (S_r, positive upwards) and the horizontal displacements (S_θ and S_λ, positive southwards and eastwards, respectively) can then be computed using ΔV and the tidal Love numbers by

$$S_r = h_2 \frac{\Delta V}{g} \tag{4}$$

$$S_\theta = \frac{l_2}{g} \partial_\theta \Delta V \tag{5}$$

$$S_\lambda = \frac{l_2}{g} \frac{1}{\sin\theta} \partial_\lambda \Delta V \tag{6}$$

When the Love number values appropriate to the pole tide, such as h_2=0.0627 and l_2=0.0836, are used, the practical estimations of the site displacements caused by the polar tides can be given by

$$S_r = -32 \sin 2\theta \left(x_p \cos\lambda - y_p \sin\lambda \right) \tag{7}$$

$$S_\theta = -9 \cos 2\theta \left(x_p \cos\lambda - y_p \sin\lambda \right) \tag{8}$$

$$S_\lambda = 9 \cos\theta \left(x_p \sin\lambda + y_p \cos\lambda \right) \tag{9}$$

The values of (x_p, y_p) are the orientation parameters of the pole with the unit of arc seconds.

It can be estimated by using the formulas that the maximum radial displacement is around 25 mm, and the maximum horizontal displacement is approximately 7 mm, as the (x_p, y_p) can vary up to 0.8″ in general [McCarthy, 1996]. One of the most important fact to the site displacements caused by the polar tides is that the displacements estimated have a non-zero average over any time span because m_1 and m_2, originally defined in equation (1) to decide ΔV, have a characteristic of non-zero average. It is, hence, important for high accuracy GPS as the adjusted coordinates are normally produced by taking the 'mean' values over the observations. In order to ensure the consistent GPS coordinate results, the effect of polar tides has to be realised and estimated during the data processing.

2.2 Atmospheric Pressure Loading

A time-varying atmospheric pressure mass can lead to crustal deformation. This displacement of the surface is at the several millimetres level, primarily in the vertical direction. Atmospheric pressure loading effects tend to be correlated over distances of approximate 1,000 km and a time-scale of approximate one week. Therefore, height estimates from a one-week duration GPS campaign may be regionally biased and perhaps tilted by several millimetres with respect to a global geocentric reference frame [Blewitt, 1994].

It has been shown that the earth's crust moves downward in response to variations in atmospheric pressure loading by approximately 0.5 mm/mbar, and the application of atmospheric loading models will significantly improve the height results [Blewitt et al., 1994]. The vertical (radial) displacement due to atmospheric pressure loading can be simply given by

$$\Delta r = \alpha \ (P - P_0) \tag{10}$$

where α is the pressure loading coefficient obtained from a table, eg in MacMillan and Gipson (1994), P is the measured station surface pressure, and P_0 is the reference station pressure. Since the vertical displacement from this calculation can be approximately represented as a simple function of site pressure, measurements of local pressure must be made at GPS stations.

Another atmospheric pressure loading displacement model mentioned in the IERS technical notes is expressed as

$$\Delta r = -\ 0.35P -\ 0.55\overline{P} \qquad (11)$$

This formula involves only the instantaneous pressure P at the site, and an average pressure $\overline{P}$ over a circular region with a 2,000 km radius surrounding the site [McCarthy, 1996]. Both pressures are pressure anomalies with respect to the standard pressure of 1,013 mbar, and the unit of the vertical displacement Δr is millimetres.

It has been found that vertical surface displacements of 20 mm caused by atmospheric pressure loading are common. The evidence also shows that the addition of oceans to the earth model has a greater effect on the loading displacement at coastal sites and at points within a few hundred kilometres of the coast [vanDam and Wahr, 1987]. One practical analysis based on a global GPS network has also indicated that atmospheric pressure loading contributions are clearly evident in GPS height measurements and the application of the loading corrections can reduce the variance of the GPS height estimate by up to 24% [vanDam et al., 1994]. Hence, atmospheric pressure loading is also an important error source when vertical station coordinate determination at a few millimetres accuracy level is required.

3. AUXILIARY DATA

During the practical tests carried out for the geophysical effects, the auxiliary data sets need to be used in the estimations of site displacements. Therefore, two types of auxiliary data based on the effects of polar tides and atmospheric pressure loading have been collected for the estimation.

For the investigation of site displacements caused by the polar tides, a set of earth orientation parameters (EOP), mainly describing the polar motion, is required. As a combined pole solution derived from various GPS series has been provided by the IERS, this weighted average of the polar motion, namely the EOP (IERS) 97 P 01, can be given at one-day intervals and used for the estimation of the effect of polar tides [Gambis and Eisop, 1997]. An example of this GPS-based pole solution is listed in Table 1 for the first three days of 1997.

Table 1 Pole solutions applied to the effect of polar tides

IERS/CB GPS Solution EOP(IERS/CB) 97 P 01						
date		mjd	x	y	ut-utc	d
1997			"	"	s	s
JAN	1	50449.5	-0.02495	0.09544	-0.112050	0.002013
			0.00003	0.00010	0.000030	0.000010
JAN	2	50450.5	-0.02861	0.09605	-0.114050	0.002007
			0.00010	0.00007	0.000021	0.000014
JAN	3	50451.5	-0.03198	0.09713	-0.116020	0.001961
			0.00012	0.00014	0.000017	0.000016

In order to estimate the effect of atmospheric pressure loading, the surface measured atmospheric pressure and the average pressure over a circular region with a 2,000 km radius surrounding the GPS site are both required. The examples of these data are listed in Table 2 and Table 3 for one-hour intervals of meteorological data measured at FLNM (Fonglin), one of the GPS permanent sites in the eastern part of Taiwan, and three-hour intervals of the average pressure collected from the meteorological sites within a 2,000 km ring around Taiwan, respectively.

Table 2 Meteorological data measured at FLNM

Time (UT) yyyy mm dd hh mm ss.ss	Dry Temp (°C)	Rel Humd (%)	Pressure (mb)
1996 07 22 00 00 0.00	29.21	64.0	997.7
1996 07 22 01 00 0.00	32.01	52.0	997.5
1996 07 22 02 00 0.00	33.51	45.0	996.7
1996 07 22 03 00 0.00	33.71	51.0	995.9

Table 3 Average pressure around Taiwan

Time (UT) yyyy mm dd hh	Site (Number)	Pressure (mb)
1996 07 22 00	14	1008.3
1996 07 22 03	15	1008.7
1996 07 22 06	17	1007.2

4. RESULTS AND ANALYSES

Coincided with the estimation of geophysical displacements, a part of the GPS permanent tracking stations in Taiwan were selected as the test points, based on their specific geographic and atmospheric conditions. The distribution of totally nine GPS tracking sites in this area, including one IGS station and eight fundamental stations (four of them were used as the test points), are shown in Figure 1.

4.1 Displacements by Polar Tides

The EOP data sets provided by the IERS with one-day intervals can be used to realise the position of pole, and to estimate the site displacements caused by the polar tides, based on using equation (7), (8), and (9) for three coordinate components. The information provided by the EOP data sets is illustrated in Figure 2 for one whole year of 1996.

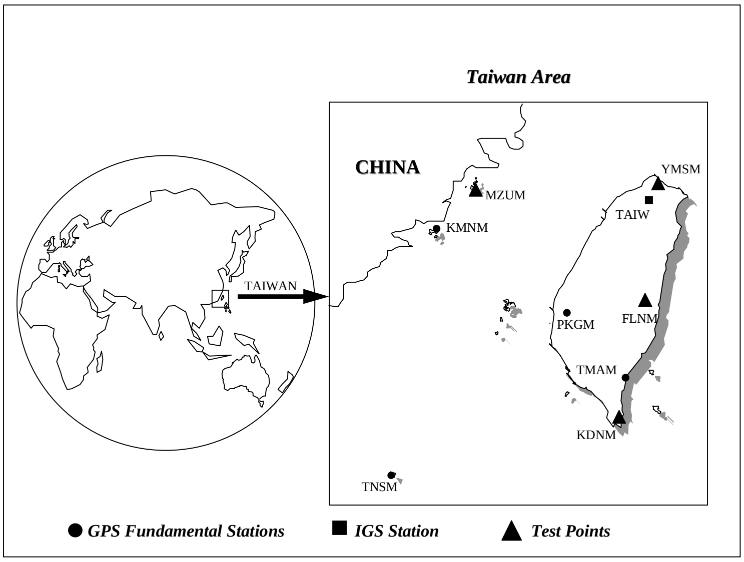

Figure 1Distribution of permanent GPS sites in the Taiwan area

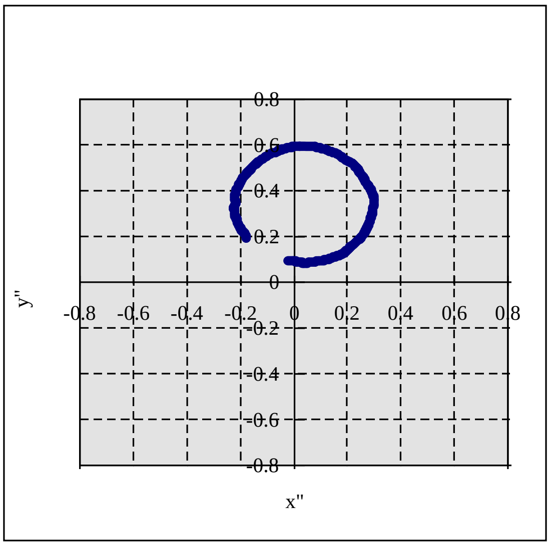

Figure 2 Polar motion in 1996

A basic concept can be proved by Figure 2 that the period of pole motion is not exactly one year. The changes of station coordinate due to polar tides will not be zero, even by averaging coordinates for one-year GPS solutions. It is particularly important for GPS data processing with any period of observations not to ignore such site displacements caused by the polar tides.

Based on the EOP data sets and models suggested by the IERS, the estimation of site displacements can be carried on for the effect of polar tides. As the effect is clearly site and time dependent, the changes of coordinate are believed to be spatially related to the site location and temporarily associated with the polar motion. The estimation has been practically tested for a GPS tacking station at YMSM (Yangming Mountain), whose latitude and longitude are relatively significant to reflect the site displacements due to polar motion in the Taiwan area. The results are now shown in Figure 3 and listed in Table 4, with the changes of coordinate in height (H), south (S), and north (N) components for the year 1996.

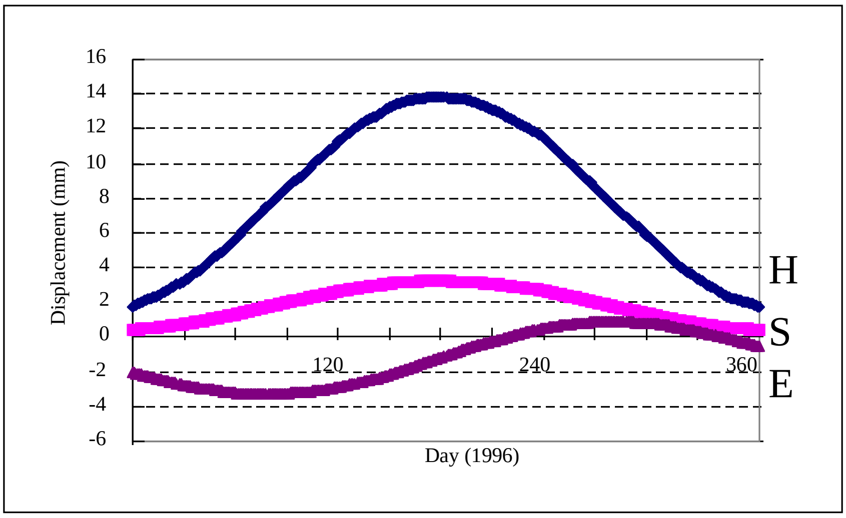

Figure 3 Displacements at YMSM due to polar tides in 1996

Table 4 Displacements at YMSM based on one-year period of polar motion

Displacement	H (mm)	S (mm)	E (mm)
Mean	8	2	-1
Std Deviation	4	1	2
Maximum	14	3	-3
Minimum	2	0	1

The influence of the effect can be seen by the statistical values shown in Table 4. The maximum horizontal displacement of 3 mm is much lower than the vertical displacement of up to 14 mm, during one year of period. Moreover, the site displacements cannot be 'averaged out' over one year period in all three coordinate components, as the mean displacements are around 2 mm and 8 mm in plan coordinates and height, respectively.

To investigate the displacements based on short period of polar motion, two other GPS permanent sites, located at KDNM (Kending) and MZUM (Mazu Island), were also selected to further test the effect of polar tides. The results based on one-month periods for January 1996 and January 1997 are shown in Table 5.

Table 5 Mean displacements at GPS sites based on one-month period of polar motion

Jan/1996	H (mm)	S (mm)	E (mm)
YMSM	2	1	-2
KDNM	2	1	-2
MZUM	3	1	-2
Jan/1997	H (mm)	S (mm)	E (mm)
YMSM	2	0	-1
KDNM	1	0	-1
MZUM	2	0	-1

It is clear to see from Table 5 that the differences of mean displacements based on one-month period are not significant between the three different GPS sites. Only 1 mm small difference can be found in height for this position-related effect over the region around Taiwan. For the displacements estimated at the same site for the same period with one year difference, an insignificant difference of 1 mm is also found in all three coordinate components. However, this level of difference is likely to be extended if this time-related effect is varied with the increment of polar motion.

Nevertheless, there is a significant level of difference in height, comparing the mean displacements shown in Table 4 and Table 5, whose values are varied up to 6 mm by estimating the effect of polar tides for different periods of observations. This is an important fact that the site displacements caused by polar tides must be taken into account when different periods of GPS data are processed together to obtain the average coordinate solutions.

4.2 Displacements by Atmospheric Pressure Loading

The vertical site displacements caused by atmospheric pressure loading can be estimated using equation (11) when pressure data required are properly collected. Two permanent GPS sites, located at FLNM and YMSM with the elevations of around 140 m and 785 m respectively, were selected to test the displacements due to atmospheric pressure loading. As this effect is obviously dependent with the meteorological condition, two data sets based on three days of meteorological measurements in January (representing winter) and July (representing summer), respectively, have been used to investigate the influence of atmospheric pressure loading on GPS height solution. The results are shown in Figure 4 and Figure 5 for the two GPS sites. Some gaps occurred in the figures were due to the lack of surface meteorological measurements at that time. The statistical values of the estimates are also listed in Table 6 for the details.

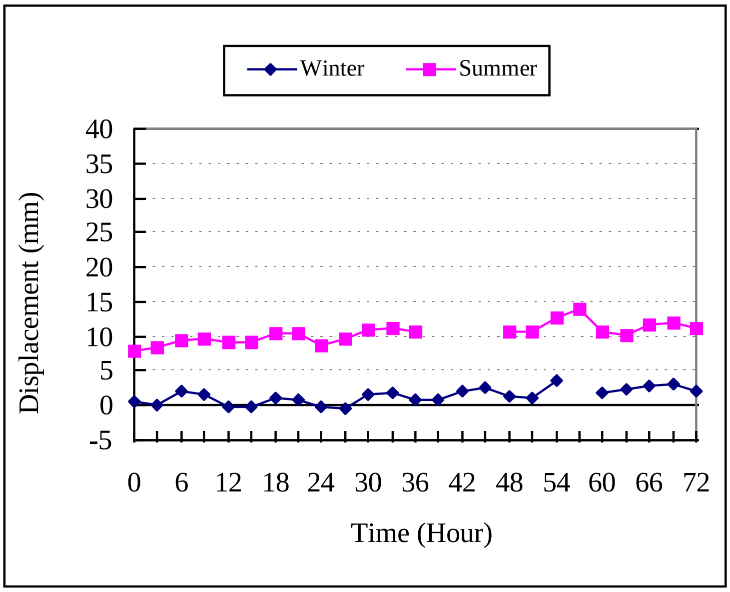

Figure 4 Vertical displacements at FLNM due to atmospheric pressure loading

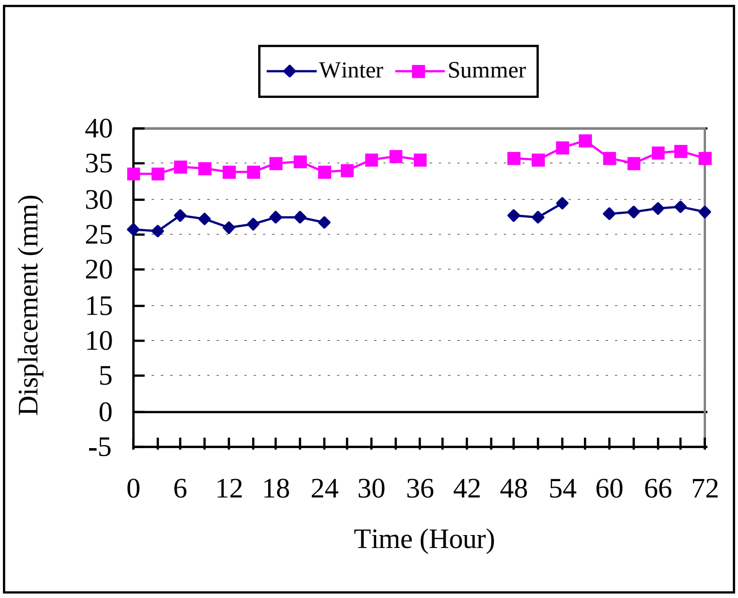

Figure 5 Vertical displacements at YMSM due to atmospheric pressure loading

Table 6 Vertical displacements at GPS sites due to atmospheric pressure loading

Winter (January)	FLNM	YMSM
Mean	1	27
Std Deviation	1	1
Maximum	4	29
Minimum	-1	26
Summer (July)	FLNM	YMSM
Mean	10	35
Std Deviation	1	1
Maximum	14	38
Minimum	8	34

(unit: mm)

It can be clearly seen from Figure 5 and Figure 6 that the effect of atmospheric pressure loading is highly correlated with the season, in which a level of 10 mm difference in vertical displacement can be found at the two sites. It can also be proved that the atmospheric pressure loading is significantly varied with the data measured in different seasons, particularly in summer and winter. The GPS solutions based on the data sets observed in different seasons, therefore, must be processed with the corrections for the vertical displacement due to atmospheric pressure loading, in order to produce the final set of GPS coordinates.

It also can be seen from the detailed values shown in Table 6 that the differences of the vertical displacements are more than 25 mm between the two different GPS sites observed in the same season. This level of displacement difference shows the importance of the implementation of atmospheric pressure loading at GPS stations whose elevations are relatively higher to easily lead to more significant pressure anomalies.

5. CONCLUSIONS AND SUGGESTIONS

(1) Based on the local scale of GPS tracking network in Taiwan, two geophysical effects, namely the polar tides and atmospheric pressure loading, were confirmed by the estimation of site displacements carried out using models recommended by the IERS and the auxiliary data collected.

(2) The displacements caused by polar tides showed an average of 8 mm height variation during one year of period. It was also proved that a 6 mm height difference exists between the displacements estimated from two different periods of data sets, based on one month and one year of polar motion, respectively. The effect of polar tides was found to be important for high accuracy GPS when different periods of GPS solutions are combined to provide the final coordinate solutions.

(3) The displacements caused by atmospheric pressure loading showed that the large differences in height are possible when GPS and meteorological measurements are made at different sites or in different seasons. The difference between the displacements based on the meteorological data collected in the two different seasons was up to 10 mm. The difference was significantly increased to 25 mm between the two different sites with the meteorological data measured at the same time. The effect of atmospheric pressure loading was found to be critical at certain GPS sites, whose pressure variations are known to be large in the Taiwan area.

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