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A GEOCENTRIC REFERENCE SYSTEM IN TAIWAN

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ABSTRACT

One of the fundamental goals of geodesy is to precisely define positions of points on the surface of the Earth, so it is necessary to establish a well-defined geodetic datum for geodetic measurements and positioning computations. Recently, a set of the coordinates established by using GPS and referred to an international terrestrial reference frame could be used as a three-dimensional geocentric reference system for a country. Such a geocentric reference system, based on this modern concept, has been carried out in 1997 and realised in 1998 for Taiwan. Besides the advantages of using GPS to effectively establish this new national reference system, the coordinate qualities of these well-distributed and well-defined GPS control stations will also benefit from the convenient implementation of the maintenance for the coordinate system.

INTRODUCTION

The horizontal and vertical geodetic datums are conventionally established and maintained through the triangulation-trilateration and levelling networks, respectively. With the advent of new observation techniques used in space geodesy, such as Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Very Long Baseline Interferometry (VLBI), and Global Positioning System (GPS), it has become possible to easily connect geodetic points and provide enough information to accurately determine their three-dimensional coordinates (X,Y,Z) in one well-defined reference frame. Once a set of ellipsoid parameters is given, the geodetic coordinates (φ,λ,h) of the points can also be decided through a simple transformation procedure.

For the establishment of the geodetic networks, one of the space geodetic techniques emerged in the 1980’s and well-developed in the 1990’s, namely the Global

Positioning System (GPS), is particularly important for its great performances on the working scale from local, regional, to global **[4]**. As the GPS receivers are relatively small, cheap, and easy to operate, the observation of geodetic networks using GPS can be effectively implemented. Most importantly, millimetre to centimetre level of positioning accuracy have been widely demonstrated over the baseline lengths from tens, hundreds of kilometres up to thousands of kilometres **[2]**. With this space geodetic technique, it has been proved to be feasible to establish a regional or continental scale of reference system by GPS observations **[9]**.

Now a new geocentric reference system can be possibly established in Taiwan by using GPS to connect its fundamental stations with some of the permanent GPS sites well-maintained by the IGS (International GPS Service for Geodynamics), whose three-dimensional geocentric coordinates are well-known in the ITRF (International Terrestrial Reference Frame). With the extensive use of GPS in the geodetic network, it provides a convenient but precise way to specific an ideal coordinate reference system for Taiwan, and the time evolution of this reference system is also easy to be taken into account.

CONVENTIONAL DATUM USED IN TAIWAN

The conventional geodetic datum used in Taiwan was based on the geodetic observations carried out in 1978, and the reference ellipsoid selected was the Geodetic Reference System 1967 (GRS67). The origin point of this datum was located at the Hu-Tzu-Shan astronomic station. The coordinate of this origin point and the initial azimuth from this point to the reference point were both based on the first-order astronomic observations.

Four other basic assumptions for this datum were also made as follows:

(1) Centre was the mass centre of the earth;

(2) Three axes were aligned parallel to the average terrestrial system;

(3) Astronomic and geodetic coordinates for the origin point kept the same;

(4) Ellipsoid was tangent to the geoid at the origin point.

Some defects can be clearly found from the definition of this datum, where the assumptions of (3) and (4) might be not true as the separation between the ellipsoid and the geoid was significantly existed.

For the geodetic measurements made for this datum, the fundamental control networks extending from Hu-Tzu-Shan station to other 2661 points of first-, second-, and third-order control stations were set up using triangular and trilateral observations. The least-squares adjustments were then carried out with the method of variation-of-coordinates for the control networks.

The coordinates, including the latitude and longitude based on the GRS67, grid coordinate based on 2°-Zone Transverse Mercator (TM) projection, and height above the mean sea level, for all the geodetic control stations were released by the Ministry of Interior in 1980. This set of coordinates used in Taiwan was called the Hu-Tzu-Shan coordinate system, also named the TWD67 (Taiwan Geodetic Datum based on the GRS67).

REFERENCE SYSTEM BASED ON GPS MEASUREMENTS

TWD67 have been used for almost two decades. Due to the occurrence of natural disaster, such as earthquake and typhoon, and many constructions undertaken in the island during this period of time, over 60% of the triangulation points, mostly below 500 metres high, were serious damaged or even lost. As many surveying campaigns still have to be carried on, the re-measurement or re-establishment for geodetic control points are therefore important to ensure their best accuracy.

This problem was found, and a working committee was organised by the government to investigate the difficulty and possibility of establishing a new geodetic control network by using satellite positioning techniques, such as GPS. When GPS observations are widely made in the geodetic network, the strategy of defining a new geodetic coordinate system is not unique. Generally, three different ways have been practically considered in this procedure:

(1) GPS data are first transformed into the ‘old’ datum system using a proper set of transformation parameters. The transformed coordinates are then combined with the existed terrestrial data, and used in the network adjustment **[1]**.

(2) GPS observations are merged with the terrestrial observations, in various forms of observation equations, to implement a re-adjustment for geodetic network, where GPS data can be used to define the orientation, scale, and origin of this ‘new’ system **[8]**.

(3) GPS data are extensively collected in the geodetic network, and GPS data are primarily processed and analysed in the network adjustment to establish a ‘new’ 3-D datum **[6]**.

A new, integrated, unified, and high accuracy GPS control network in Taiwan is of importance at this time. More importantly, if a GPS-related reference system is established, the significant differences of up to 1000 metres between the horizontal coordinates based on WGS84 and TWD67 could be much improved across the island. This implies a solution for the navigation applications or the integration of digital data sets, whose coordinate sources are mostly based on GPS.

When a new geocentric reference system defined in Taiwan by GPS measurements, many advantages can be seen from its observation, data processing, coordinate accuracy, and future application. Those benefits are now summarised as follows:

(1) Easy operation, automatic data processing, reliable and high accuracy coordinates can be achieved by GPS;
(2) Three-dimensional coordinates can be defined in a unified reference system;
(3) The parameters of axes orientation, scale, and origin, used to define a traditional datum, can be implicitly replaced by a three-dimensional coordinate data set;
(4) Stations located in Taiwan and its offshore islands can be connected and unified into a same coordinate system;
(5) Three-dimensional geocentric coordinates and curvilinear geodetic coordinates can be mutually transformed through a simple mathematical procedure;
(6) A geocentric datum based on a global point of view can be achieved and used for the international applications;
(7) GPS observations and coordinates derived can be used for different scales of geodetic networks, extending from a local, regional, to global positioning.

This nationwide coordinate reference system based on GPS observations will be defined as a unified geodetic datum in Taiwan and its offshore islands, which is not the case in TWD67. Nevertheless, the recommendations made by the IERS (International Earth Rotation Service) also encourage national agencies to establish their precise national datums based on ITRF in order to be linked into regional or continental solutions and used for many international applications **[7]**. This new established reference system for Taiwan will, therefore, meet with the requirement of defining a geocentric datum based on a global point of view. However, a geocentric ellipsoid, says GRS80, will also be selected to relate rectangular with curvilinear geodetic coordinate, which is still widely used in the geodetic applications.

NEW COORDINATE SYSTEM IN TAIWAN

The final strategy was made by the working committee to establish a fundamental GPS network consisting of 8 permanent tracking stations, 105 first-order, and 621 second-order GPS control stations in Taiwan area. This proposal was approved by the government in 1993. The detailed schedule was to set up 4 of GPS permanent stations in 1993 and 4 others in 1994, to carry out 105 first-order GPS control stations in 1995, and to implement 621 second-order GPS stations through 1996 to 1998, all by GPS.

Based on the concepts and advantages mentioned above for the establishment of a geocentric coordinate system using GPS, a complete procedure implemented in Taiwan is described as follows:

(1) To set up a fundamental GPS network consisting of 8 GPS tracking stations, 105 first-order GPS control stations, and 621 second-order GPS control stations in Taiwan area (see Figure 1 for the distribution of GPS tracking stations, and Figure 2 for the distribution of first-order GPS control stations).

(2) To realise the high accuracy three-dimensional geocentric coordinates and velocity fields for GPS tracking stations, by connecting with some selected IGS sites whose coordinates are well-defined in the ITRF94.

(3) To achieve a high accuracy three-dimensional coordinate data set for all the GPS control stations through a rigorous GPS network adjustment, based on using dual-frequency carrier phase data observed by static GPS.

(4) To chose GRS80 as the reference ellipsoid for coordinate converting between the rectangular coordinate of (X,Y,Z) and the curvilinear coordinate of (φ,λ,h).

(5) To adopt Transverse Mercator projection for plane coordinate converting. The grid coordinates of (N,E) are calculated by defining with a 2-degree zone, and using 121°E and 119°E as the central meridians for Taiwan and its offshore islands, respectively.

MAINTENANCE FOR GPS CONTROL STATIONS

When a national coordinate system is established by using high accuracy GPS positioning, a procedure designed for its regular maintenance is also required. It is aimed to ensure the quality and accuracy for the GPS control stations as they might be degraded by any intended or natural effects.

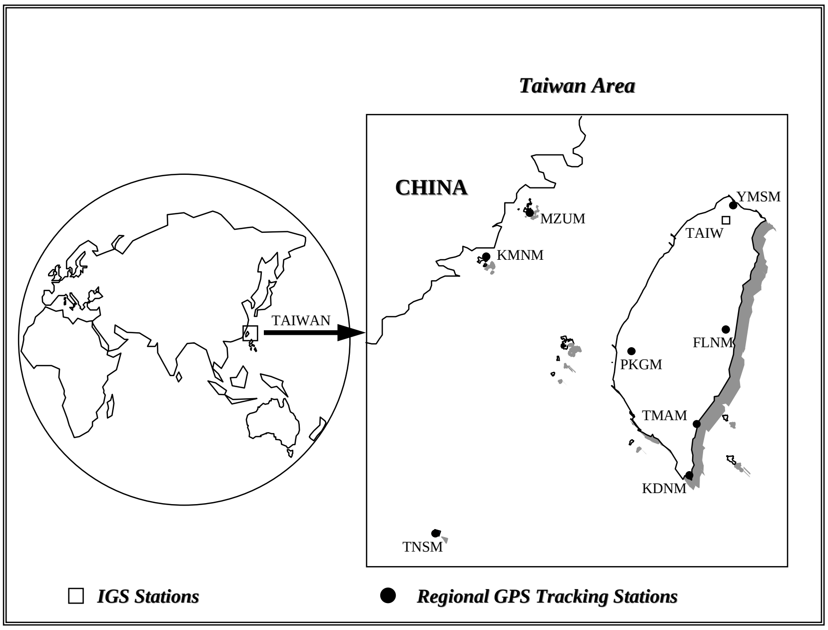

Fig. 1. GPS tracking stations in Taiwan area

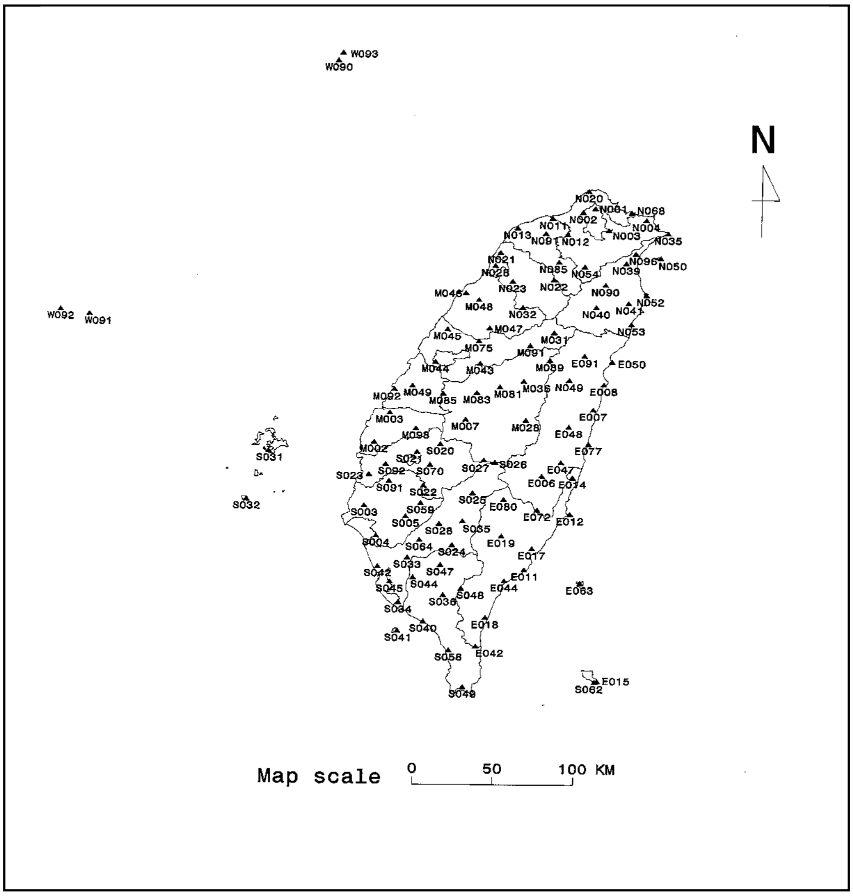

Fig. 2. First-order GPS control stations in Taiwan area

The GPS control stations set up to define a so-called geocentric reference system in Taiwan can be classified into three levels, namely GPS tracking stations, first-, and second-order GPS control stations. Their geographic distributions, operational functions, and coordinate accuracies have all been well-designed.

As Taiwan is located at the fringes of different tectonic plates, the coordinates of GPS sites are significantly affected by crustal deformation or tectonic plate motion **[5]**. If the regular maintenance is not made for those GPS sites, the geocentric reference system based on this fundamental GPS network would be distorted. However, if the maintenance is frequently carried out for those GPS control stations, it would also result in some difficulties for land planning and management as the coordinates of these control stations have to be jointly changed. Therefore, a guideline set up to carry on a stable frequency and consistent quality of maintenance for the GPS control stations in Taiwan is particularly required.

For the maintenance of GPS tracking stations in Taiwan, the accurate coordinates of these GPS tracking stations are determined in the network adjustments integrating with part of the IGS stations whose coordinates are regularly maintained with the realisation of the ITRF. If the tracking sites are permanently operating and their coordinates are routinely computed, it is implied to have maintenance for those of the GPS tracking stations. When a long term of coordinate data sets are archived for GPS tracking stations, they can be used to investigate the time evolution. As the coordinates of the first-order GPS control stations are determined by fixing the coordinates of the GPS tracking stations in the network adjustments, the information of time evolution provided by the GPS tracking stations can be used to carry on the maintenance for the first-order GPS control stations in Taiwan.

In order to also investigate the strain and stress models caused by the motion of tectonic plates and crustal deformation in Taiwan area, a monitoring network consisting of several GPS sites must be established to routinely and accurately provide the coordinate variations for the sites. The GPS sites operating for this monitoring network can be designed by three categories, composing of the GPS tracking stations set up by the Ministry of Interior to provide their continuously tracking data, part of the GPS monitoring stations operated by the Academia Sinica to collect the longer term of data from some specific sites where the crustal deformation has shown to be active over the decade, and part of the first- or second-order GPS control stations to carry on the periodic GPS campaigns. This integrated monitoring network will be then expected to play a main role on the maintenance work for the geocentric reference system in Taiwan.

SIMULATION TESTS FOR COORDINATE QUALITY

In order to realise the effects of coordinate variations in the fundamental GPS network, the simulation tests were carried on for some selected GPS control stations. The sites, whose coordinates were fixed in the simulation tests, were composed of the eight GPS tracking stations and one IGS site in Taiwan area. Seven first-order GPS control stations were also selected as the test points to carry on adjustments individually with all the GPS tracking stations. These test points used in the simulation tests are now shown in Figure 3.

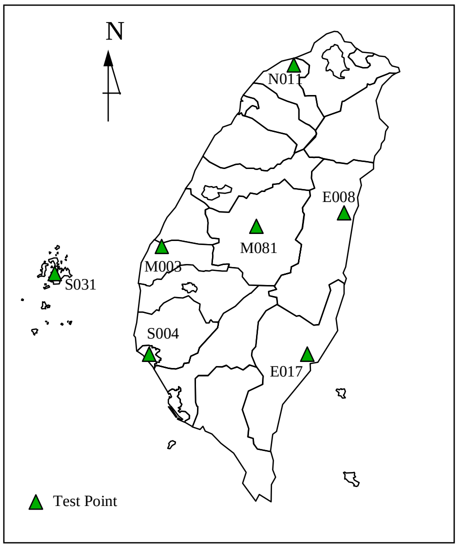

Fig. 3. Distribution of seven test points

The basic observation used in the network adjustment was the Cartesian coordinate vector of the baseline between the fixed stations and each test point. The observation error was simulated by multiplying a factor to the coordinate posterior precision. The coordinate variations, based on the velocity fields of the GPS tracking stations, were also taken into account in the network adjustments, as

$$\Delta X(t_c)=(X^1(t_0)+V^1(t_c-t_0))-(X^2(t_0)+V^2(t_c-t_0)) \qquad (1)$$

where, $\Delta X(t_c)$ is the baseline vector at epoch t_c, $X^1(t_0)$ and $X^2(t_0)$ are the coordinates of the two ends of a baseline at reference epoch t_0, and V^1 and V^2 are the moving velocities of coordinates decided at reference epoch. The time span considered for the coordinate variations was on a basis of five years. The velocity fields used for the coordinate variations were estimated with the data collected at each GPS tracking station from 1995 to 1997.

Based on the error tolerance set up for the tests, the ratio of the residual to the standard error of the residual must be less than 2, i.e. $V/\sigma_V \leq 2$. It is found from the preliminary network adjustments that the test value is always over the error tolerance for the baseline where the tracking station of TNSM is a part of it. It is believed to be the reason that the coordinate accuracy of this site is relatively worse than those of the other tracking stations due to the worse data quality collected at the site. It is also obvious to find out that the TNSM station, which is 570 km apart from the Taiwan island, is a significant defect in the network configuration due to its long baseline length. It is, hence, decided to reject TNSM station from the network tested for further adjustments.

One other evidence is then found from the tests that the Y coordinate component for the test points M003, M081, N011, S004, and S031 is significantly affected by the tracking station PKGM after one year‘s coordinate variations. It is clear to show the importance of maintenance for the coordinate of PKGM, which is seriously moved by the land subsidence to the site **[3]**.

As the coordinates of the stations fixed in the network adjustments are moved with the velocity fields, the coordinate variations are also appeared to the test points in the network adjustments. Their coordinate differences, based on the variations of 5 successive years, are now listed in Table 1 and shown in Figure 4 with the RMS (Root-Mean-Square) values for all the test points.

Table 1. *RMS coordinate variations for the test points*

Time Span (year)	N(cm)	E (cm)	H (cm)
1	0.2	1.1	2.1
2	0.6	3.4	4.7
3	1.1	5.7	7.3
4	1.5	8.0	10.0
5	1.9	10.3	12.6

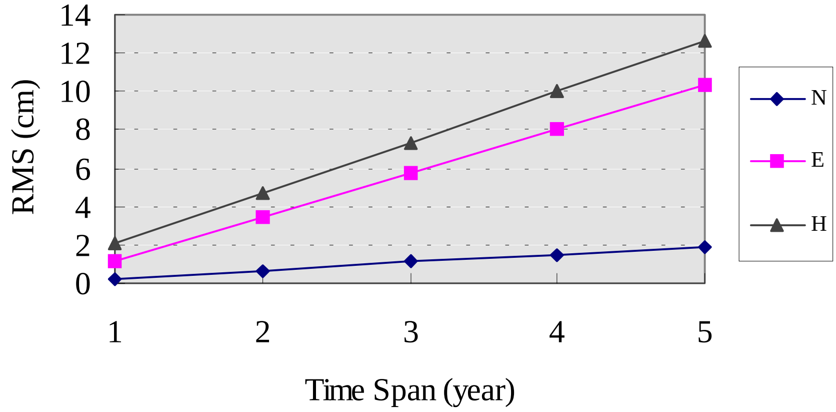

Fig. 4. RMS coordinate variations in three coordinate components

It can be seen from the results that the network adjusted coordinates of the test points have shown a different level of variations on different coordinate components for different time spans, when the coordinate variations occurred at the GPS tracking stations are taken into account. A consistent variation is seen on each coordinate component, but the height is clear to has the most significant variation, whose coordinate changing rate is up to 2-3 cm per year. The variation in the E-W component also shows an impressive level of coordinate difference by around 2 cm per year. However, the N-S component has the most stable variation as its coordinate changing rate is nearly 0.5 cm per year and a significant level of variation will not be seen in five-year time. These preliminary test results are then expected to provide a valuable information for setting up a guideline to carry on maintenance for the new coordinate system in Taiwan.

CONCLUSIONS AND SUGGESTIONS

The establishment of a geocentric reference system using GPS, and the long term maintenance for the coordinate system in Taiwan are both essential to some of the scientific and engineering applications, in which the high accuracy coordinates are particularly required.

It has been mentioned that such a new coordinate system, based on a geocentric reference system measured by GPS, has been carried out and realised in Taiwan. Moreover, the coordinates of those GPS tracking stations are expected to be regularly maintained by cooperating with the IGS sites, which are well-maintained in a global terrestrial reference frame. The effects of network configuration defined by the geometric connections between the GPS tracking and control stations, and the coordinate variations caused by the tectonic motion or crustal deformation to the GPS sites are also important to be investigated for the maintenance work.

Five points are also proposed as follows, and expected to be discussed to carry on the maintenance for the new coordinate system in Taiwan :

(1) How to monitor the variations of coordinates to assess the quality of the coordinates prior designed for the system;

(2) How to select and ensure a proper number and well-distributed GPS control stations to maintain the basic function, stability, and consistency for the system;

(3) How to update the coordinates of the GPS control stations, and how to provide the transformation parameters between the two coordinate data sets for the system;

(4) How to carry on re-observation or re-establishment for the stations whose sites or quality are damaged or lost;

(5) How to mutually provide any updated or the latest information about the coordinate quality between the system manager and users.

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