APPLICATION OF A GPS-BASED METHOD TO TIDAL DATUM TRANSFER

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Abstract

Observations of the tide are required for the reduction of bathymetric soundings, as each measured depth must be reduced to a tidal datum. If there are no fixed tide gauges located in or near the project area, an auxiliary recording gauge could be installed at a central point and usually operated for 30 days to determine a tidal datum for hydrographic surveys. Alternatively, some computation methods are available to transfer a well-defined datum from fixed tide stations close to the project area. The efforts involved in eliminating such datum errors must be made to ensure the precise bathymetric measurements. Estimates have shown that the datum errors caused by three short-term tide observations, based on 30, 60 and 90 days, are approximately 10cm in the Taiwan area. Moreover, four traditional computation methods for tidal datum transfer have also been tested to compare the results with those of the GPS-based geometric interpolation method. The results indicated that the GPS-based method is able to provide the most reliable tidal datum, with an average accuracy of around 3cm. This is believed to be sufficient to meet the requirements of a 5cm level of tidal error for Special Order of hydrographic surveys.

Introduction

The nautical chart, based on high accuracy bathymetric measurements, is of particular importance for major trading nations such as Taiwan. A great demand is placed on hydrographic surveyors to provide high accuracy, up-to-date charts for both navigation systems and various engineering applications.

Echo sounding is the most effective technique for collecting massive quantities of bathymetric data. Soundings for hydrographic surveys are measured by echo sounders which record a nearly continuous profile of the seabed below the survey vessel. The echo sounders measure the time required for a sound wave to travel from the transmitter to the seabed and return. The time is then converted to distance, or depth, by multiplying by the velocity of sound in water. Soundings are recorded at regular intervals, sufficient to provide a realistic representation of the bottom topography.

Tidal or sea level observations are required for the reduction of the bathymetric soundings, as each measured depth must be reduced to the datum of reference, i.e. the tidal datum, for the particular area (NOS, 1976). The so-called tide, or water level, reduction is made by applying the difference between the height of the tide, or water level, and the datum of reference at the time when the sounding was made. A tide, or water level, recording gauge is generally used for this purpose (Ingham, 1975). If there are no fixed tide gauges located in or near the project area, an auxiliary recording gauge may be installed at a central point and operated for at least 29 days to establish a tidal datum applied for the hydrographic surveys (USACE, 2001).

Owing to the fact that tidal differences commonly exist across the area being surveyed the tide measured at an auxiliary gauge may not truly reflect the tide required for sounding reductions. Therefore systematic datum errors at the auxiliary gauge site have to be avoided to ensure high precision bathymetric measurements. Practically, the datum errors chiefly depend on the validation of the tidal data and the effectiveness of the transfer methods, as only short period of tidal observation is normal, and the functions used to connect a datum with the nearby permanent gauges are theoretically not perfect.

In order to investigate the datum errors, three short periods of tide observations, extending from 30 days to 60 days and up to 90 days, were computed by the authors in order to estimate the errors related to the availability of the tidal data. Four traditional methods for tidal datum transfer, namely levelling height difference, simultaneous observation, range ratio and least squares water level were also studied to compare those results with the datums derived from the tidal computation. A so-called GPS geometric interpolation method, using GPS height solutions referred to the WGS-84 ellipsoid and a linear interpolation between the tidal stations, was also proposed and tested in the Taiwan area. This GPS-based geometric interpolation method was expected to provide an acceptable accuracy for tidal datum transfer. When this proposed method is applied, the GPS height solutions can support high accuracy transfer information and the linear interpolation can reduce the transfer function errors to effectively extend a known tidal datum from the permanent gauges to the project site.

Tidal Datum and Transfer Methods

Datum Definition

As previously mentioned, the recorded soundings made in hydrographic surveys must be corrected for any departure from true depths, such as transducer draft and reduction to reference datum (Chang, et al, 2002). The tide reductions are generally derived from data recorded by tide gauges mounted on piers close to the project area, so the relationship between the water level and tidal datum has to be established and realised.

A vertical datum is defined as a level from which heights or depths are measured (see Figure 1). To establish a vertical datum, a time series of tidal data collected at a fixed gauge is required. The length of the series varies depending on the accuracy requirements e.g. one to three months of data for engineering projects and 19 years of long-term observations for the establishment of a stable vertical reference (DeLoach, 1995).

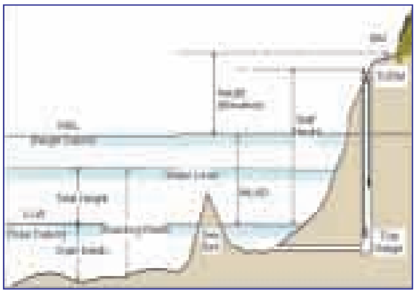

Figure 1: Tide levels and vertical datums

On land the orthometric height system, in which the geoid or equivalently mean sea level (MSL) is defined as the vertical datum, is popularly used. A bench mark (BM) is then fixed to the ground and used as a 'real' reference to the vertical datum by establishing the relationship between the tide gauge bench mark (TGBM) and the tide staff with precise levelling.

A tidal datum is normally adopted in hydrographic charting and used as a reference from which to reckon depths of seawater. In the waters around Taiwan, the tidal datum has been defined as lower low water (LLW) and all sounding data is reduced to this water level. To use such a reference surface, a local site is normally built in the project area in order to take a specific series of tidal observations, generally over at least one month. If only a few days of observations are available, the simultaneous observations taken at a long-term tide gauge site may be used to transfer its tidal datum to the project area (NOS, 2000a).

Factors affecting the accuracy of datum transfer include the length of each data series used to compute the datums, geographic locations, tidal characteristics or sea level trends in the region, and the reference stations used. Based on all of these error factors, the accuracy of datum transfer can be expected to be ±3cm to ±8cm (NOS, 2000b). Hence, it can serve as a useful quality control standard for an operational datum reference transferred from a permanent gauge to the project area during hydrographic surveying.

Conventional Transfer Methods

Ensuring the establishment of a proper tidal datum is the initial task of hydrographic surveys. In practice, operating a tide station with short-term tide observations at the project site is essential. A more accurate tidal datum can then be obtained by using nearby primary tide stations, operated simultaneously, to adjust those short-term readings to the 19-year equivalent. When tidal characteristics are assumed to be the same at the sites and the levelling fieldwork is not too costly, a levelling-based method linking the project site to any known tidal datum is usually adopted. If tidal characteristics between the sites are assumed to be changing at a fairly constant and linear rate, a linear interpolation between the project site and two existing sites whose tidal datums were previously determined could be further performed (USACE, 2001).

To carry out such datum transfers, simultaneous short-term tide observations at the project site (auxiliary tide station) and a control site (permanent tide station) are normally required. When the tidal datum at the project site is related to those of the control sites, the investigation of the datum errors caused by using any transfer method is of importance (Greenfeld, 2002; Liu, 2000). Some conventional methods typically used to establish a tidal datum in locations that are remote from the long-term recorded tide stations but close to the project areas are summarised and tested in this paper. The geometric relationship between two known tidal datums at the permanent gauge sites and a tidal datum to be estimated at the auxiliary station is plotted in Figure 2.

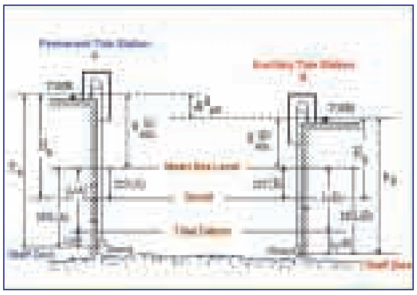

Figure 2: Geometric relationship for datum transfer

Referring to Figure 2 and assuming that SST(A)=SST(B) and L(A)=L(B), the basic equations for tidal datum transfer methods applied to a auxiliary tide station are listed and explained as follows:

Levelling Height Difference Method

$$L_0(B) = E_B - E_A + MSL(A) - \triangle H_{AB} - L(A) \qquad (1)$$

When the relevant datum parameters, i.e. E_A, MSL(A), L(A), have been established at the long-term tide station A, this method can be applied to determine the datum parameter of $L_0(B)$ at the auxiliary tide station B, only if the staff length of E_B is observed at site B and the height difference between site A and site B, i.e. $\otimes H_{AB}$, is measured by levelling.

Simultaneous Observation Method

$$L_0(B) = [MSL(A) - msl(A)] + msl(B) - L(A) \qquad (2)$$

This transfer method is based on the geometric operation that the difference values between the long-term and short-term mean water level at tide station A, i.e. MSL(A)-msl(A), are the same as those observed at tide station B. If the tide observations are simultaneously recorded at the auxiliary tide station B for 30 days, its short-term mean water level, i.e. msl(B), can be combined with the datum parameters of station A to derive the local datum parameters of station B.

Range Ratio Method

$$L_0(B) = [MSL\ (A) + \triangle H_{AB}] - \frac{R_B}{R_A}.L(A) \qquad (3)$$

This is believed to be a common method for computing the tidal datum parameters at an auxiliary tide station. To apply this method, a simultaneous period of observations has to be made at the permanent and auxiliary tide stations for at least 3 to 6 days. The range ratios required by this method, i.e. R_A and R_B, are defined as the observed ranges from high water level to low water level at the tide stations.

Least Squares Water Level Method

$$L_0(B) = \frac{R_B}{R_A}.L_0(A) - \triangle H_{AB} \qquad (4)$$

This operation is very similar to the range ratio method, only with the introduction of a minimum concept to deal with the tidal datum as a special low water level. The advantage of using this method is that the mean water level observed at long-term tide station A is not required.

GPS-based Method

It is now common to build GPS stations at or near tide gauges around the world for geodetic and oceanographic applications (Chang, 1995; Robert & Merry, 2001; Bevis, 2002). Consequently, a so-called GPS geometric interpolation method is therefore proposed by the authors to measure the height of tide gauge bench mark (TGBM) at both the long-term and auxiliary tide stations with respect to the GPS datum of the WGS-84. The tidal datum, such as mean lower low water (MLLW) used in the Taiwan area, is then connected to the ellipsoid at the long-term tide station and transferred to the auxiliary tide station as necessary. As static GPS can easily provide accurate height difference solutions between sites, more than one long-term tide station located close to an auxiliary site can be measured simultaneously in order to carry out a distance-weighted linear interpolation and thus estimate a more reliable tidal datum for the auxiliary site.

Basically, this GPS-based method is supposed to reduce the estimation errors for tidal datum transfer based on few technical reasons. As mentioned above, more than one permanent tide station can be easily observed by using GPS to provide the datum connecting information for control. The datum estimation errors resulting from the different tidal curves between the long-term and auxiliary tide stations can be relatively reduced. In the case of using two permanent tide stations to estimate tidal datum in between, this 'interpolation' type of linear operation is assumed to minimise the inconsistency of the tide curves, as opposed to the 'extrapolation' type used by the conventional transfer methods with only one control site. In addition, the tidal datums are all referred to the ellipsoid for transfer so that the mean water level is no longer required by making any simultaneous tide observations. This GPS-based method is therefore expected to mitigate the transfer errors and simplify the fieldwork associated with short-term tide observations and levelling measurements.

This GPS-based method is actually adapted from the levelling height difference method and combined with a linear interpolation in order to play a more economic and accurate role in tidal datum transfer. An operational diagram illustrating the geometric relationship between TGGS (tide gauge GPS station), TGBM and DL (datum level), based on the WGS-84 ellipsoid, is shown in Figure 3.

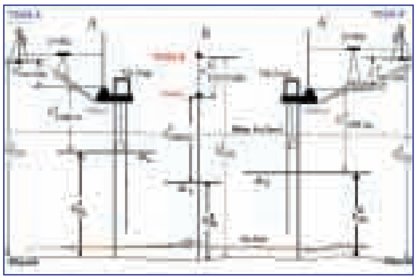

Figure 3: Geometric relationship for GPS-based datum transfer

As can be seen from Figure 3, two permanent tide stations at A and A' and an auxiliary station at B are simultaneously measured with static GPS. The geometric heights of TGGSs, i.e. h^A_{TGGS}, $h^{A'}_{TGGS}$ and h^B_{TGGS}, can be obtained from the GPS solutions. The TGGSs are also connected with TGBMs by precise levelling to establish the vertical information, e.g. $H^A_{TGGS-TGBM}$, $H^{A'}_{TGGS-TGBM}$ and $H^B_{TGGS-TGBM}$. When vertical ranges between DL and TGBM, i.e. $H^A_{TGBM-DL}$ and $H^{A'}_{TGBM-DL}$, are provided by the long-term tide observations for the two control sites, the most important heights of DL above ellipsoid, i.e. h^A_{DL} and $h^{A'}_{DL}$, are finally obtained for datum transfer. These geometric equations are now expressed as follows:

$$h^A_{DL} = h^A_{TGGS} - (H^A_{TGGS-TGBM} + H^A_{TGBM-DL})$$

$$h^{A'}_{DL} = h^{A'}_{TGGS} - (H^{A'}_{TGGS-TGBM} + H^{A'}_{TGBM-DL}) \qquad (5)$$

A distance-weighted interpolation using GPS baseline lengths from A and A' to B, i.e. d_{AB} and $d_{A'B}$, is operated with the heights of DLs derived from Equation (5). The geometric height of DL at the project site, i.e. h^B_{DL}, is then established by using such a linear interpolation. The vertical range from DL to TGBM at project site B, i.e. $H^B_{TGBM-DL}$ used in practice, is estimated in reverse from GPS solutions and levelling data. These interpolation and estimation procedures are expressed as follows:

$$h^B_{DL} = \frac{h^A_{DL} \cdot d_{A'B} + h^{A'}_{DL} \cdot d_{AB}}{d_{AB} + d_{A'B}}$$

$$H^B_{TGBM-DL} = h^B_{TGGS} - H^B_{TGGS-TGBM} - h^B_{DL} \qquad (6)$$

Results and Analysis

Test Areas and GPS Surveys

The use of GPS measurements at tide gauge sites has been proposed and tested to enable the tidal datum transfer from the permanent sites to any auxiliary site. This was to be achieved by testing a number of tide stations, with different tidal variation trends, among three selected areas along the western coast of Taiwan (see Figure 4).

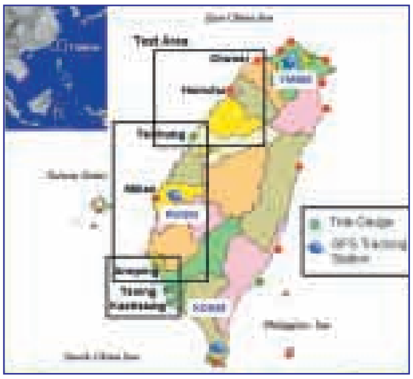

Figure 4: Seven test sites distributed at three categorised areas

The basic set-up for determining the heights of TGBMs in a geocentric reference system and transferring tidal datum from two permanent stations to one target site can be seen in Figure 3. The implementation procedure is that a TGGS has to be established for each tide station, as close to tide gauge as possible but in a location suitable for GPS measurements. Then, the heights of the TGGSs are referred to a geocentric reference system, such as the TWD97 used in Taiwan, by linking to several GPS tracking stations, e.g. YMSM, PKGM and KDNM as shown in Figure 4 (Chang and Tseng, 1999). This is followed by a local precise levelling, so that the heights of the TGBMs and tidal datums are connected to the TGGSs and also referred to the ellipsoid.

A total of seven selected tide stations on the western coast of Taiwan were investigated. The selection of the tide station was based on the principle that each site should have long-term tidal data, in order to determine a reliable tidal datum for its comparison with the transferred datum. It was expected that insignificant differences would occur between the computed and GPS transferred datums, thus the accuracy of the transfer technique could be assessed.

The GPS campaign took place from 7th-9th August 2001. One of the standard ASHTECH-Zsurveyor receivers was used at all of the tide gauge GPS stations. The campaign was carried out over three consecutive days, i.e. one session per test area, with 6 hours of GPS observations, a 15-second data interval and a 15-degree elevation cut-off angle being employed. The data processing for the GPS campaign was carried out using the commercial software GeoGenuis 2000. The three single-session networks were individually linked to a nearby GPS tracking station, but jointly processed with the use of IGS precise ephemeris, L1/L2 frequency combination, modified Hopfield atmospheric model and antenna phase centre correction.

The GPS solutions were then obtained from the three independent single-session networks. Since two of the sites - Taichung and Annping - were involved in two different sessions, the so-called session-to-session agreement, defined as the coordinate discrepancy between the two single-session GPS solutions for the same site, is regarded as an indicator of internal accuracy at centimetric level.

It must be admitted that the analysis of internal accuracy based on just two stations is hardly a convincing statistical estimate. However, this test was chiefly carried out to understand the effectiveness of using the GPS technique for tidal datum transfer. As a result, the GPS networks were only designed to have a

Station	Session	GPS Height (m)	Agreement (cm)
Taichung 1	22.045	1.4	
	2	22.031	
Annping	2	22.380	2.6
	3	22.354	
Average			2.0

Table 1: Session-to-session agreements for GPS heights

general level of accuracy for engineering applications. The vertical components of the GPS solutions and coordinate agreements are shown in Table 1.

The session-to-session vertical agreements represent the quality of the solutions from the three-session GPS observations, with the average of 2.0cm in height. This level of coordinate agreement evidently still has room for improvement in accuracy, but it is believed to be beneficial in the validation of using GPS solutions for tidal datum transfer.

Tidal Computations Using Short-term Data

Tidal data with more years of observations can theoretically provide a more reliable tidal datum. Chen (1996) estimated the datum biases for tide gauges in China and found that the biases in datum determination were reduced to 5cm if 5-year tidal data was used, whereas an error level of 60cm existed with the use of just one month of tidal data.

For logistical and financial reasons, many hydrographic surveys are conducted with just one-month of tidal observations to establish the tidal datum in the project area. This part of the test was carried out for some selected sites in Taiwan in order to investigate the biases of datum determination using short-term tidal data by comparing them with those derived from the long-term data sets.

Three subsets of tidal data were computed and tested, based on a completed 7-year data set collected from 1992 to 1998. Considering the typical working seasons for hydrographic surveys in the Taiwan area, the three periods for tidal computations were selected, namely 1 month, 3 months (from June to August) and 6 months (from May to October), over the same period of 7 years. In each period of tidal datum computations, three selected tide gauge sites, (Hsinchu, Taichung and Kaohsiung) were used. In order to assess the datum biases, three short periods of datum estimates were compared with those using the full period of long-term tidal data. The results derived from these tests are shown in Table 2 and Figure 5.

It can be seen from Table 2 and Figure 5 that the comparisons between the different periods of data show a total range of 7-14cm difference in datum biases for all three test sites. It was also found that

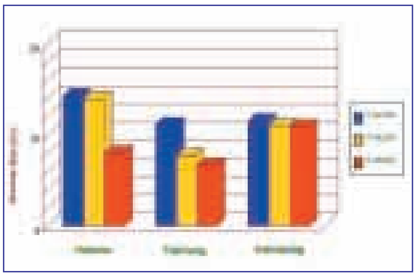

Figure 5: Tidal datum biases for the data period tests

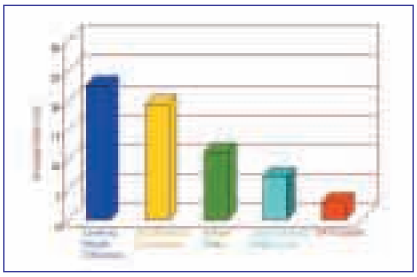

Figure 6: Tidal datum biases in average for the transfer model tests

the lowest bias was achieved with a 6-month data period. The estimated datum biases are slightly degraded to an average of 12cm for the 1-month data period and 11cm for the 3-month data period, reducing to 9cm for the 6-month data period. If a maximum tidal error of 10cm as suggested by the IHB (1998) for other order surveys is adopted, the test results show that the widespread use of a 30-day tidal observation period in datum determination would not appear to yield a sufficiently reliable estimate. Even though an average bias of 8.5cm was achieved using a 6-month data set, it is still not assured of meeting the 5cm tidal error requirement for the Special Order surveys.

Datum Determinations with Transfer Models

The tidal datum is generally established using a 30-day tidal data set recorded at the project area. It is however believed that the datum transfer methods, relying on other reliable tidal datums set up at nearby permanent tide gauge sites, is capable of reducing the tidal datum biases. In order to test this theory, several types of transfer models have been considered. These include the comparison of datum biases estimated by the proposed GPS-based method with those computed by the traditional transfer models, namely the levelling height difference (LHD), simultaneous observation (SO), range ratio (RR) and least squares water level (LSWL) methods.

Based on the tidal data recorded in 1998, three selected tide gauge sites were tested once again in order to estimate the tidal datum biases for the transfer models used. The transfer-derived datums, based on the traditional methods using 30-day tidal data and the GPS-based method using 6-hour GPS measurements, were all compared with those 'known' datums computed using the longest period of tidal observations at sites. The discrepancies between the transferred datums and the known datums at the test sites are indicators of datum biases related to the transfer models. The results are shown in Table 3 and Figure 6.

For those datum biases estimated using the traditional methods, the values listed in Table 3 generally show a larger level of bias than those listed in Table 2 resulting from tidal computations with 30-day tide observations. However, the level of bias value is still lower than the biases obtained by the least squares water level method. These levels of bias, less than 10cm, are slightly better than those computed using up to 6 months of tide observations at the test sites.

The test values also demonstrate that the absolute datum biases estimated using the GPS-based geometric interpolation method are generally in accord with the datum given by the long-term tidal computations. It can be seen from Table 3 and Figure 6 that GPS-derived datum biases show the best performance among these transfer models, with a maximum bias of around 5cm and an average bias of around 3cm. This level of bias in tidal datum determination is believed to be sufficient to meet the requirements for a Special Order hydrographic survey.

A further investigation of this GPS-based method was carried out for some available combinations of the tide stations shown in Figure 4. The test results obtained by either an interpolation or extrapolation type of datum transfer, using GPS solutions to connect each test site with two nearby reference sites whose tidal datums are known by the long-term tidal computations, are shown in Table 4.

From Table 4 it can be seen that an absolute mean bias of approximately 3cm exists between the two sets of datum values in this comparison. The largest biases caused by applying the GPS-based transfer model are 5cm at Taichung and 7cm at Annping. This correlates with the fact that these two test sites used the other two reference sites located in the areas with inconsistent tide variation trends, as indicated in Figure 4, for the areas classified. However, the test results still appear to be a random variable with no indication of systematic biases caused by

Station	Data Period		
	1 month	3 month	6 month
Hsinchu	14.3	13.9	8.1
Taichung	11.1	7.8	6.7
Kaohsiung	11.5	11.0	10.8
Average	12.3	10.9	8.5

Table 2: Absolute biases for the data period tests (unit: cm)

Model	Station			Average
	Hsinchu	Taichung	Kaohsiung	
LHD	32.2	12.8	22.7	22.6
SO	16.9	19.8	24.4	19.5
RR	7.2	12.2	7.3	11.3
LSWL	4.6	7.6	9.5	7.2
GPS	2.1	5.1	2.3	3.2

Table 3: Absolute biases for the transfer model tests (unit: cm)

Test Site	Reference Site	Distance (km)	Datum Transferred (m)	Datum Known (m)	Bias (cm)
Kaohusiung	Tsoing Annping	9.2 41.9	1.892	1.869	2.3
Tsoing	Kaohusiung Annping	9.2 32.7	2.052	2.070	-1.8
Annping	Tsoing Miliao	32.7 87.8	1.808	1.739	6.9
Miliao	Annping Taichung	87.8 68.2	5.626	5.652 -2.6	
Taichung	Miliao Hsinchu	68.2 73.5	6.083	6.134 -5.1	
Hsinchu	Taichung Chuwei	73.5 44.2	6.212	6.191 2.1	
Chuwei	Taichung Hsinchu	117.7 44.2	4.762	4.796 -3.3	
Absolute Average					3.4

Table 4: Tidal datum biases for the GPS-based transfer method

the GPS-based transfer model. This experiment proved the effectiveness of the use of GPS solutions in a tidal datum transfer process, as opposed to any other traditional transfer models, and also confirmed the merit of the GPS-based method for the tidal datum determination without taking any short-term tide observations at project sites.

Conclusions

This paper has discussed the preliminary results of the application of a GPS-based datum transfer model for hydrographic surveys, in terms of the determination of a tidal datum required for the project area. Some concluding remarks on this subject can be drawn as follows:

- Tidal datums are frequently computed using 30-day tide observations at the project site, or adopting some traditional models to make a transfer from another tide gauge site whose tidal datum has been well estimated using its long-term tidal data. Higher biases and more fieldwork are inevitable when using this method of datum determination and it is not acceptable for high accuracy hydrographic surveys.
- The use of GPS measurements at project sites now offers a level of accuracy, typically 2cm, which enables the tidal datum to be effectively transferred from other well-established tide stations without taking a period of tide observations at the project sites.
- The datum biases were estimated to be approximately 12cm, based on tidal computations using 30-day data sets, for the selected test sites along the western coast of Taiwan. Using the simultaneous tide observations made at project sites and nearby permanent tide stations, the traditional transfer models resulted in datum biases of 7-23cm, which does not correspond so well with a long-term datum.
- The effect of the GPS-based geometric interpolation method was confirmed when the same sites were tested to make a transfer for the tidal datum. The results consistently indicated datum biases of 2-7cm for each site, corresponding well with the 3cm average with for long-term datum. This indicates that the GPS-based model could be a realistic option for tidal datum transfer, having both logistical and financial benefits and ensuring the high accuracy hydrographic surveys.

biography

Chang, born in 1961, holds a PhD in space geodesy from the University of Nottingham (UK). He became an associate professor at the Chung Cheng Institute of Technology, Taiwan, in 1996, soon after he returned from the UK and was further promoted to a full professor and served as the geodetic group leader of the department in 2000. Dr Chang has published around 90 journal and conference papers in various geodetic fields, such as precise positioning techniques, movement monitoring, control surveys, navigation safety assessment and hydrographic surveys - mainly based on GPS technology. He has also been invited to be the consultant to many government institutions in Taiwan, such as the Hydrographic Bureau and Land Survey Bureau. Now he is also a directing board member to some local academic societies, such as the Geoinformatic Society and National Defence Society based in Taiwan.

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