PRELIMINARY TEST OF TIDE-INDEPENDENT BATHYMETRIC MEASUREMENT BASED ON GPS

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ABSTRACT

A GPS system was designed to carry out so-called 'tide-independent' bathymetric measurement, in order to compare with the conventional technique in which the tidal observations are made at tide gauges along the coast. Through the estimation and introduction of attitude parameters and height corrections, both based on the GPS solutions, the tide-independent bathymetric measurement can be implemented without making any direct tidal observation. The data set was collected by the field test on the northwestern coast of Taiwan. The preliminary results show that the measurement quality has been effectively improved by using the proposed tide-independent technique. The bathymetric accuracy, estimated from the check points, indicated an improvement of between 7% and 26%, depending on whether the attitude correction was applied or not applied. This level of accuracy satisfies the first-order standard required for hydrographic surveys.

1. 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 and up-to-date charts for both navigation systems and various engineering applications.

As the survey vessels normally take bathymetric measurements in a 'dynamic' environment on the sea surface, it is almost impossible to instantaneously collect the 'ideal' vertical measurements related to the mean sea level. This difficulty, however, can be solved with mathematical methods by introducing attitude parameters of the vessel (roll, pitch, heading, and heave) into the bathymetric corrections [Blagoveshchensky, 1962].

GPS has been the most important advance in space positioning techniques over the last two decades. A multi-antenna GPS system, which can be easy-mounted on a vessel, has proved to be able to precisely determine its attitude parameters through the combinations of the GPS vectors [Rapatz, 1991; Lu and Cannon, 1994; Ziljoski, et al., 1999; Chang, et al., 2001].

Moreover, the reduction of bathymetric measurements to the datum of reference requires the tidal reduction of depths, typically using tidal data collected by tide gauges [Ingham, 1975]. A so-called 'tide-independent' technique, based on using GPS height solutions to connect all measurements, was proposed and tested by the authors. The bathymetric measurements obtained by this GPS-based technique are expected to replace those derived with height corrections relying on tidal data read from pier-mounted tide gauges [Phelan, 1998]. The accuracy assessment of the bathymetric measurements, made by both the conventional and GPS-based techniques during the field test, has been possible using some check points.

2. CONVENTIONAL BATHYMETRIC MEASUREMENT

Echo sounding is the most effective technique for collecting massive quantities of bathymetric data. Soundings for hydrographic surveys are measured by echo sounders that record a nearly continuous profile of the sea bottom below the survey vessel. The echo sounders measure the time required for a sound wave to travel from the transmitter to the sea bottom 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.

Electrical energy pulses can be converted to acoustical energy by a transducer mounted in the vessel's hull. The transducers with various frequencies are used for different ranges of depth, such as using low-frequency pulses for sounding in deep water. The depths of water measured by echo sounders are actually depths below the transducer, not depths below the water surface. The so-called static draft, as an echo sounding correction, refers to the depth of the transducer below the surface of the water when the vessel is not underway. The static draft of the hydrographic vessel must be further combined with the effects of settlement and squat, caused by various vessel speeds, for the total dynamic draft correction to compensate for vertical displacements and changes in attitude when the vessel is underway [USNOS, 1999].

The tide or sea level observations are also required for the reduction of the bathymetric soundings, as each measured depth must be reduced to the datum of reference, i.e. the sounding datum, for the particular area [USACE, 1991]. The so-called tide, or water levels, 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. If there is no fixed tide gauges located in or near the project area, an auxiliary recording gauge could be installed at a central point and operated during the entire period of the hydrographic survey.

As already mentioned, the recorded soundings made in a hydrographic survey need to be corrected for any departure from true depths, such as the transducer draft and the reduction to datum of reference. The mathematical relationship for a tide-dependent bathymetric measurement is shown in Figure 1, and express as

$$d = (v \times t/2) + d_t - h_{tide} = d_{obs} + d_t - h_{tide} \qquad (1)$$

where d is the reduced bathymetric measurement required, v is the velocity of sound in water, t is the time for the pulse to travel to the sea bottom and return, d_t is the transducer draft, h_{tide} is the tide observation of the elevation of the water surface above (or below) the sounding datum, and d_{obs} is the depth measurement made by the sounder.

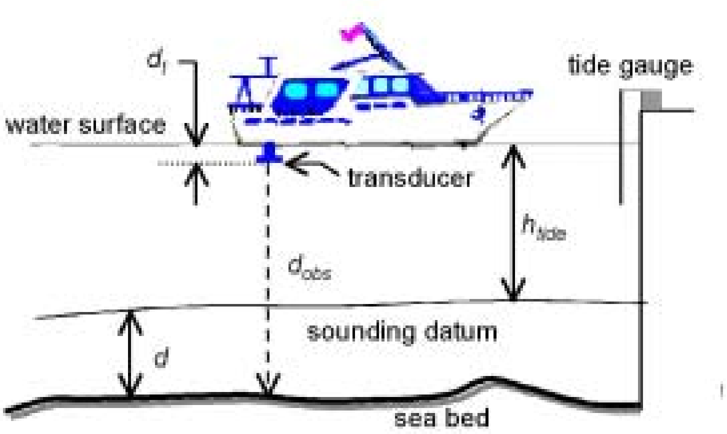

Figure 1 Tide-dependent bathymetric measurement with corrections

3. TIDE-INDEPENDENT BATHYMETRIC MEASUREMENT

As early mentioned, in the conventional tide-dependent bathymetric measurement, all soundings must be corrected for the height of the tide above (or below) the sounding datum for the project area. The tide reductions are generally derived from data recorded by tide gauges mounted on piers and close to the project area. Due to the fact that tide height differences normally exist across the area being surveyed, the tide measured at a gauge may not truly reflect the tide required for sounding reductions. Therefore, the accuracy of the available tidal data may be not sufficient to derive precise bathymetric measurements.

A so-called tide-independent bathymetric measurement is proposed, using kinematic GPS to measure the height of the water surface with respect to the WGS-84 ellipsoid. The sounding datum, mean lower low water (MLLW) adopted for use in the Taiwan area, is also connected to the ellipsoid by using static GPS at the tide gauge bench mark (TGBM) in order to obtain its geometric height. The instantaneous height of the water surface can then be referred to sounding datum through the use of GPS vertical solutions without taking the need to make tidal observations.

The geometric height of the GPS antenna (h_{GPS}) needs to be combined with the depth measured by the transducer (d_{obs}), the offset between the GPS antenna and the transducer (d_{offset}), and the ellipsoid height of the sounding datum (h_{sd}), in order to satisfy the geometric condition necessary for the tide-independent bathymetric measurement. The relationship is shown in Figure 2, and expressed as

$$d = d_{obs} + d_{offset} - h_{GPS} - h_{sd} \tag{2}$$

where d denotes the reduced bathymetric measurements.

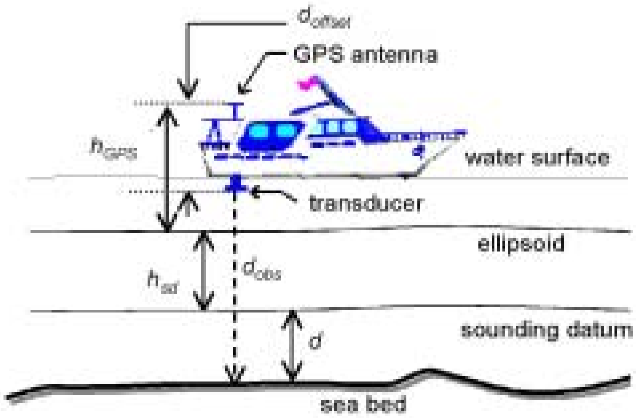

Figure 2 Tide-independent bathymetric measurement based on the use of GPS

4. SYSTEM OPERATION AND FIELD TEST

To realise the technique in practice, and in order to assess the improvement of data quality for the tide-independent bathymetric measurement, a field test was arranged offshore of Hsinchu Harbour on the northwestern coast of Taiwan. Besides the transducer, a multi-antenna GPS system was installed and operated on a light vessel (see Figures 3 and 4), normally used by the Navy for field work in the shallow seas around Taiwan. GPS system served the determination of the three-dimensional coordinates for each antenna, at each measurement epoch.

A tide gauge GPS station (TGGS) was set up very close to the TGBM, to be used as a base station for post-processing of the kinematic phase solutions for the GPS antennas onboard the vessel. The high accuracy coordinates of the TGGS have been determined relative to a first-order GPS control station in the so-called 'TWD97' three-dimensional coordinate system of Taiwan [Chang and Tseng, 1999]. The ellipsoidal height of the TGGS was also linked to the TGBM by a local precise levelling survey, so that the sounding datum originally connected to the TGBM could also be related to the ellipsoid.

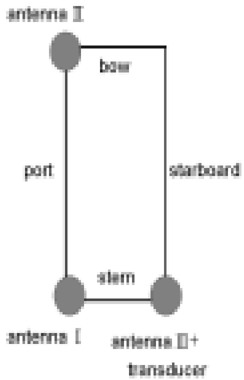

Figure 3 GPS antenna configuration on the vessel

Figure 4 GPS system operated during the field tests

Following with the installation of the onboard GPS system, the vessel was berthed against the pier in order to collect GPS data for a period of time. The same procedure was repeated when the vessel returned from the test area. The GPS data collected during these two periods of observation, less influenced by waves and surges, can be processed to estimate the relative vectors between each onboard GPS antenna in order to establish the geometric relationship between the GPS antenna platform and the vessel. The attitude parameters obtained from these two sets of initial observations were treated as a base solution for other ‘relative’ attitude parameters estimated from the successive GPS data collected during the field test.

A four-hour field test was carried out on 12 October 1999 with a sea state of wind 5-6 and gust 8 in scale. Four dual-frequency GPS receivers, two Ashtech Z-Surveyor and two Leica SR-9500 receivers, were used with a 10-second recording interval. The tidal observations recorded by the met office were also used in order to perform conventional bathymetric measurements for accuracy comparison and assessment with the proposed tide-independent technique.

The bathymetric measurements were mainly made in an offshore area approximately four kilometres from the Hsinchu Harbour (see Figure 5). A bar check was carried out in the harbour for the calibration of the transducer prior to use, and a route designed for the collection of cross check data was followed by the vessel. Unfortunately, the actual route, as can be seen in Figure 6, was not completely as planned due to the PC being used for depth data collection becoming damaged by sea water.

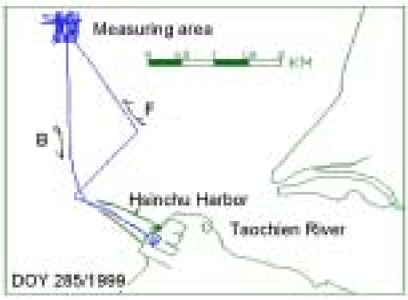

Figure 5 Vessel track across the field

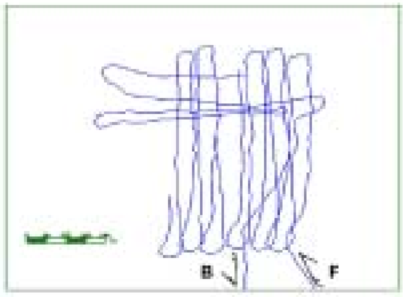

Figure 6 Vessel route for cross checking

5. RESULTS AND ANALYSIS

The bathymetric reductions, based on using bathymetric data and carrier phase-based kinematic GPS solutions, were assessed in order to determine the effectiveness of using GPS for such applications. The indicator of accuracy is simply defined as the difference in bathymetric value for each check point selected from the cross check data. The first-order standard specified by the International Hydrographic Bureau was adopted for these assessments [IHB, 1998].

According to the IHB specification, the measuring point with a horizontal distance of less than 5 m along the cross check routes was selected as the check point and assumed to have the same bathymetric measurement. A total of seven check points were found from the field test data sets. According to the IHB standards, the depth of water is around 30-40 m over the test area so that the absolute difference in bathymetric measurement for each check point must be less than 63 cm. In other words, the bathymetric measurement will be qualified with the accuracy required only if the bathymetric absolute difference is no more than 63 cm at each check point.

The bathymetric reduction models, based on using conventional bathymetric measurement (with tide observations) on the one hand, and GPS-based tide-independent bathymetric measurement on the other hand, were both applied. The test results for those measurements which have been further corrected with attitude parameters, as well as not corrected, are summarised in Tables 1 and 2 respectively.

Table 1 Accuracy test for bathymetric corrections (when attitude corrected)

Assessments	Conventional	GPS-based
Min. Absolute Difference (cm)	8.0	0.7
Max. Absolute Difference (cm)	78.0	57.9
Average Absolute Difference (cm)	29.0	27.0
Improvement Relative to Conventional (%)	N/A	7
Accuracy Satisfaction (Point Ratio)	6/7	7/7

Table 2 Accuracy test for bathymetric corrections (when attitude not corrected)

Assessments	Conventional	GPS-based
Min. Absolute Difference (cm)	15.6	2.2
Max. Absolute Difference (cm)	80.9	89.2
Average Absolute Difference (cm)	51.2	38.0
Improvement Relative to Conventional (%)	N/A	26
Accuracy Satisfaction (Point Ratio)	5/7	5/7

The accuracy improvement shown in Table 1 and Table 2 is the percentage of average absolute differences obtained by the GPS-based technique, reduced relatively from those based on the conventional tide-dependent bathymetric measurement. The accuracy satisfaction ratio is the number of successful check points over the total (7).

Compared to the values listed in Table 1, a higher level of measurement error is apparent in Table 2. This reflects the importance of applying the attitude parameters of row, pitch, and heave of the vessel for bathymetric correction. The attitude parameters solved from the multi-antenna GPS vectors are auxiliarily shown in Figures 7, 8 and 9.

The attitude variations have a standard deviation of 4.5 degrees in roll, 1.7 degrees in pitch, and around 24 cm in heave. They are believed to be generally larger than those values estimated from inshore measurements, mainly since the flat-bottom type of vessel in use is more sensitive to the sea state.

As the GPS-based bathymetric measurement is mainly expected to be able to reduce the tidal errors caused by shore-based tidal observations, the accuracy improvement from the conventional to the GPS-based bathymetric measurement, as shown in Tables 1 and 2, is estimated to be about 2-13 cm or 7-26%, depending on whether the attitude correction is applied, or not.

The conclusion that can be drawn from Table 1 is that introducing attitude correction and applying tide-independent technique for bathymetric correction, both based on using a kinematic GPS system, appears to provide accurate and reliable bathymetric measurements.

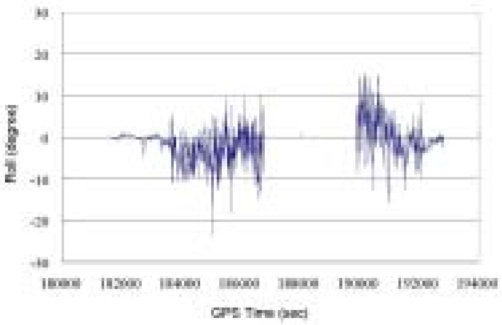

Figure 7   Variations of roll angle estimated from the GPS data

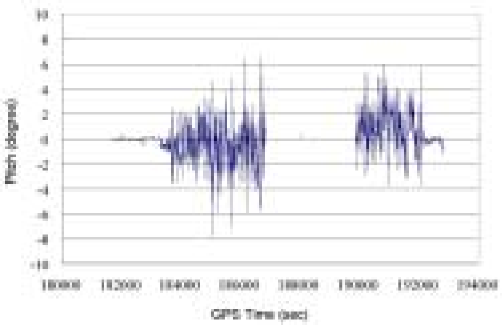

Figure 8   Variations of pitch angle estimated from the GPS data

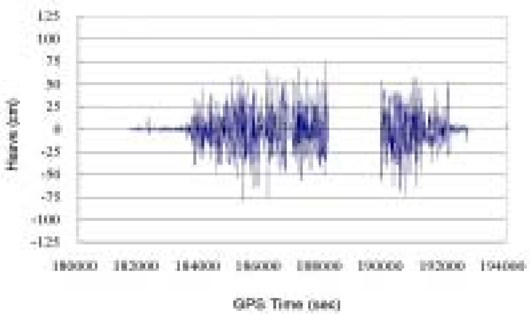

Figure 9   Variations of heave range estimated from the GPS data

6. CONCLUDING REMARKS

This paper has discussed the preliminary results of the application of a vessel-based GPS system for hydrographic surveys, particularly for the collection of tide-independent bathymetric measurements. The vertical solutions of the onboard GPS antennas can replace tide gauge observations for the reduction of bathymetric measurements to the chart reference datum. The tidal error can be reduced, and the accuracy of measurement can be improved. The attitude correction, also based on the kinematic GPS solutions from a multiple antenna configuration, has shown to have an important role in bathymetric data correction.

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