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Evaluation of GPS-Based Attitude Parameters Applied to Bathymetric Measurements

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Abstract: As the survey vessels normally take bathymetric measurements in a 'dynamic' environment on the sea surface, the attitude parameters of the vessel are basically required to be introduced into the bathymetric corrections to achieve the 'ideal' vertical measurements related to the sounding datum. 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. This study aimed at evaluating such a GPS-based system to determine the attitude parameters for the survey vessels, based on the data collected both in-land for testing and on-sea for practical use. The precision of the estimates was realized to be around 1.6′ for heading, 2.3′ for pitch, 9.9′ for roll, and 0.3 cm for heave, based on the testing data. When system was practically applied to the bathymetric measurements made on-board, the sea depth agreements for the check points can be improved by a significant level of 43%, if a complete set of attitude parameters was in use. As the attitude information was proved to be helpful for the bathymetric measurements, it can be suggested that a multi-antenna GPS system is an economic and effective tool for the determinations of the attitude parameter, and particularly suitable for the applications of hydrographic surveys.

Key words: multi-antenna GPS system; attitude parameters; bathymetric measurements

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0 Introduction

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 sounding datum. This difficulty, however, can be solved with mathematical methods by introducing attitude parameters of the vessel (heading, roll, pitch and heave) into the bathymetric corrections [1].

It is easy to realize that the attitude parameters of the vessel are varied with the sea state and the weather, e.g. the heave range would be around 10-20 cm in a condition with a smaller scale of wave, but it would be increased to 60-70 cm in a different sea state with a larger scale of wave. Another case can be appeared to a vessel that the roll and pitch angles are possible up to 10 degrees over an area with an average sea depth of 20 m. Moreover, it is also estimated that the positions of vessel may be displaced by 3.5 m, and the depths may be biased by 0.3 m at each measuring point. It is generally believed that higher sea depth, more bathymetric errors influenced by the attitude parameters.

Traditionally, a well-equipped survey vessel must carry the inertial system, motion sensor and other electronic instruments to provide the information of the attitude parameters. Those sensors, normally expensive and not portable, are basically mounted on heavy tons of vessels only, and not suitable to be used over the shallow seabed, such as the area in the Taiwan Strait. Over the recent years, it is believed that GPS has been the most important advance in space positioning techniques. A multi-antenna system based on GPS, which can be easy-mounted on a vessel, has proposed to precisely determine its attitude parameters through the combinations of those GPS vectors [2] [3] [4] [5] [6].

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If a multi-antenna GPS system is carried by a vessel to obtain its attitude parameters, the direct benefit goes to the accuracy improvement for the bathymetric measurements, as the attitude-related errors can be effectively reduced. Moreover, the allowable working days for a hydrographic survey campaign can be increased, as the measurements are expected to be more reliable than those without inducing the attitude corrections. It is also capable of managing the engineering progress more easily, as the working disturbance from the sea state and weather can be relatively lowed down to have a minimum impact on the field works.

As a result, the error reductions of the bathymetric measurements require the attitude parameters to obtain the vertical measurements. A multi-antenna GPS system, based on using GPS vectors between the antennas on board, was proposed and tested by the authors. The bathymetric measurements obtained by introducing the corrections from GPS-based attitude parameters are expected to be more accurate than those derived without making any attitude corrections. The accuracy assessment of the bathymetric measurements, made by attitude parameters applied or not applied during the field test, has been implemented using some check points.

1 Attitude Parameters Determination

The vessel's antenna platform can be defined by three non-collinear points fixed on its body which were represented by the phase centers of three GPS antennas mounted on board. The baseline vector formed by antenna 1 and 2 is designed to be parallel to the vessel's longitudinal axis, i.e. the *Y*-axis of the antenna platform, and its perpendicular line towards to antenna 3 is defined as the *X*-axis of the antenna platform (as Fig. 1) [7]. The three-axis attitude angles of the antenna platform can then be determined by using such two GPS baseline vectors [4].

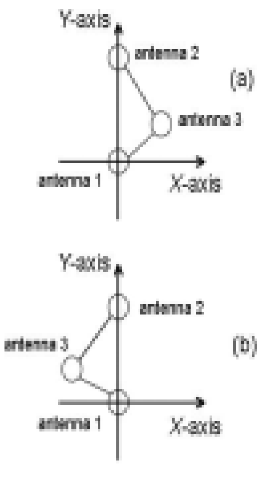

Fig. 1 Diagram of platform using three GPS antennas

The vectors of (dX_{12}, dY_{12}, dZ_{12}) and (dX_{13}, dY_{13}, dZ_{13}) must be determined from the antenna phase centers between antenna 2, 3 and antenna 1, respectively, based on their precise 3-D Cartesian coordinates. Those two vectors are then transformed into a local horizontal coordinate system, composed of east, north and up (dE_{1i}, dN_{1i}, dU_{1i}) and referred to the antenna 1, using its geodetic coordinates (φ, λ) with the following rotation [6]:

$$\begin{bmatrix} dE_{1i} \\ dN_{1i} \\ dU_{1i} \end{bmatrix} = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\sin\varphi\cos\lambda & -\sin\varphi\sin\lambda & \cos\varphi \\ \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\lambda \end{bmatrix} \begin{bmatrix} dX_{1i} \\ dY_{1i} \\ dZ_{1i} \end{bmatrix} \quad (1)$$

The heading (ψ), pitch (θ) and roll (ϕ) of the vessel can then be obtained from the GPS-based vectors of (dE_{12}, dN_{12}, dU_{12}) and (dE_{13}, dN_{13}, dU_{13}) using the following formulas [8]:

$$\psi = -\tan^{-1}\left(dE_{12} / dN_{12}\right) \quad (2)$$

$$\theta = \tan^{-1}\left(dU_{12} / \sqrt{dE_{12}^2 + dN_{12}^2}\right) \quad (3)$$

$$\phi = -\tan^{-1}\left(dU''_{13} / dE''_{13}\right) \quad (4)$$

where the components of (dU''_{13}, dE''_{13}) are specially obtained by rotating the vectors of (dU_{13}, dE_{13}) with the matrix *T*, composed of the angles of heading and pitch, as follows:

$$T = R_1(\theta)R_3(\psi)$$

$$= \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\cos\theta\sin\psi & \cos\theta\cos\psi & \sin\theta \\ \sin\theta\sin\psi & -\sin\theta\cos\psi & \cos\theta \end{bmatrix} \quad (5)$$

For the purpose of determining the vertical movement of the vessel above the water surface, the height component of the GPS solution is applied, as it is directly linked to the parameter of heave. Based on the data collected by the GPS receivers and antennas on board, the height component of each epoch solution or the height difference between the two consecutive epoch solutions is able to be used to determine the parameter of heave [4].

2 Tests for System Operation

For the system test, GPS static observations were made on land to compute the 3-D coordinate components epoch-by-epoch with carrier phase ambiguities fixed to integers using a post-processing OTF (on-the-fly) technique. The relative coordinate components from each antenna to the base antenna were then transformed into the local vector components and solved for the 'simulated' attitude parameters of heading, pitch, roll and heave.

Five dual-frequency GPS receivers were used for the system test. One site was selected as the base station for its well-defined coordinates, and occupied during the whole session. Four other sites were located around 250 m apart from the base station, and designed as Fig. 2 to perform a GPS multi-antenna system. The test campaign was carried out with 1.5-hour GPS observation, a 10 seconds data interval and 10 degrees elevation cut-off angle used. The GPS antenna platform was actually kept fixed during the observations. It was expected that insignificant attitude parameters would have varied from the averages during the test campaign, thus the zero variation could be identified and the precision of the GPS-based attitude parameter could be assessed.

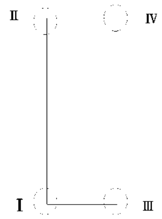

Fig. 2 GPS antennas platform used for the test campaign

The reliability of attitude parameters obtained by the multi-antenna GPS system is basically relied on the precision of GPS solution, where the data processing techniques used are important. It is generally believed that the static mode of GPS solution is more precise than those based on a kinematic mode. In order to realize the precision of phase-based attitude parameter obtained by the OTF technique, the data collected at the test campaign has been processed both by using a static mode to compute the 'standard' solutions and a kinematic mode to solve for the epoch solutions.

Using the four GPS antennas, it was possible to form four antenna combinations, i.e. antenna I-II-III, I-II-IV, I-III-IV and II-III-IV. As depicted by Fig. 2, the y-axis of the platform was defined using the longer baselines of antennas I-II or III-IV. It was obvious that a redundant fourth antenna was available at the test, leading to the possibility of computing more than one set of attitude estimates and obtaining a precision estimate for the attitude solutions.

To carry on the precision estimation, the attitude parameters determined using the OTF mode of processing technique can be compared with a 'base' solution obtained using a more accurate of static mode, defined as the mode-to-mode agreements for the attitude parameters. Moreover, another type of precision estimate can be provided by comparing the results between those obtained from different combinations of GPS antennas and a 'base' solution referred to the reference antenna system of I-II-III, defined as the platform-to-platform differences for the attitude parameters. The precision indicators of GPS-based attitude parameters for the test campaign are presented with Tab. 1.

The deviations of OTF-based attitude parameters from the GPS static solutions in heading, pitch and roll angles, based on antenna I-II-III, are shown in Fig. 3, Fig. 4 and Fig. 5, respectively, for the epoch solutions. The deviations of heave ranges, based on the antenna I, are also plotted in Fig. 6.

Tab. 1 Precision indicators for the test campaign

attitude parameter	mode-to-mode agreements			platform-to-platform differences
	min. avg.	max. avg.	rms	rms
heading (')	-3.9	2.4	1.6	2.7
pitch (')	-6.2	6.5	2.3	3.3
roll (')	-25.8	24	9.9	8.5
heave (cm)	-1.0	0.9	0.3	0.6

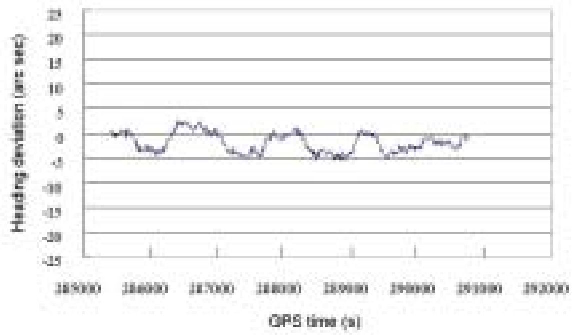

Fig. 3 Deviations of heading angle estimated from the test campaign

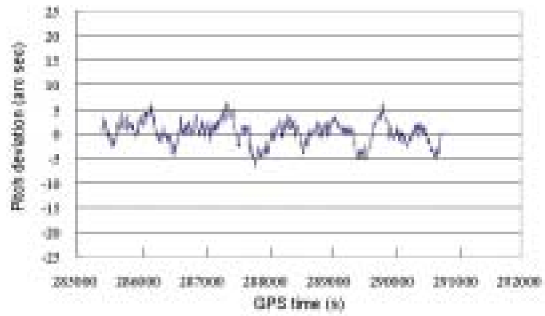

Fig. 4 Deviations of pitch angle estimated from the test campaign

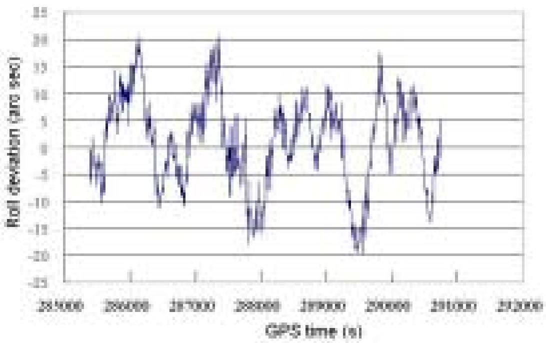

Fig. 5 Deviations of roll angle estimated from the test campaign

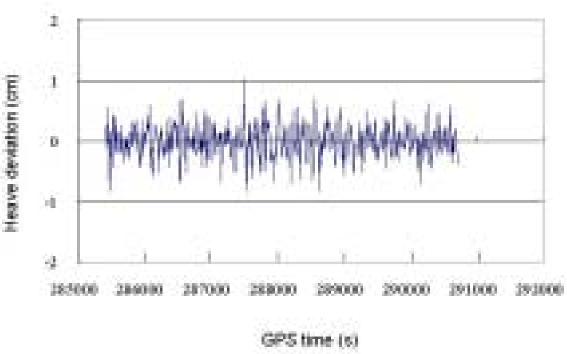

Fig. 6 Deviations of heave range estimated from the test campaign

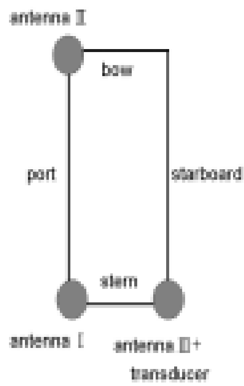

Fig. 7 GPS antenna configuration on the vessel

Fig. 8 GPS system operated during the field tests

As can be seen from Tab. 1, the mode-to-mode attitude agreements confirm the good quality of the kinematic GPS estimates obtained from the test campaign, with RMS agreements of 1.6’, 2.3’ and 9.9’ in heading, pitch and roll, respectively. The platform-to-platform differences also indicate that the attitude parameters determined from the different combinations of GPS antennas are typically consistent in three angular parameters. The heave ranges generally show that the GPS system is able to measure the ship, moving up and down, with a centimeter-level precision.

From Fig. 3, Fig. 4 and Fig. 5, it is also found that the deviations of roll are significantly higher than those of heading and pitch. Such different scales of deviation occurred in three angular parameters are explained to be that the attitude estimation errors are inversely proportional to the length of the GPS baseline and dependent with the use of the vector components. It is easy to realize that the deviation of heading would be the lowest as the longer baseline, such as antenna I-II, is used for the estimation, and the vector component of dU, normally a larger scale of positioning error existed, is not introduced by the attitude estimation as Equation (2). Oppositely, the highest scale of deviation is expected to occur in the estimation of roll, as the shorter baseline of antenna I-III and larger scale of positioning error in dU are both appeared in Equation (4), and a rotation of matrix is further applied as Equation (5).

3 Field Tests at Offshore Area

To realize the multi-antenna GPS system in practice, and in order to assess the improvement of precision for the bathymetric measurement, a field test was arranged offshore of Hsinchu Harbor on the northwestern coast of Taiwan. Besides the transducer, a multi-antenna GPS system was installed and operated on a light vessel (see Fig.s 7 and 8), normally used by the Navy for field work in the shallow seas around Taiwan. GPS system was designated to serve 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 tide gauge bench mark (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’ geocentric coordinate system of Taiwan [9]. 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.

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 well 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 implement the conventional bathymetric measurements.

The bathymetric measurements were mainly made in an offshore area approximately four kilometers from the Hsinchu Harbour (see Fig. 9). A bar check was carried out in the harbor 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 Fig. 10, was not completely as planned due to the PC being used for depth data collection becoming damaged by sea water.

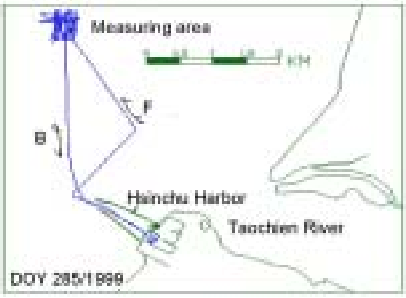

Fig. 9 Vessel trajectory across the field

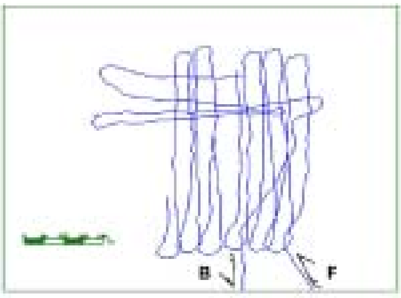

Fig. 10 Vessel route for cross checking

4 Results and Analysis
4.1 Attitude Determinations

The attitude parameters solved from the multi-antenna GPS vectors are now shown in Fig. 11, Fig. 12 and Fig. 13. It can be seen that the attitude variations have a range of ± 6 degrees in pitch, ± 10 degrees in roll and around ± 75 cm in heave. It is also realized by comparing Fig. 11 and Fig. 12 that the roll angles are generally larger than those of pitch, mainly caused by the error budget and the flat-bottom type of vessel in use. Statistically, those angle variations showed a standard deviation of 2 degrees in pitch and 3 degrees in roll, and a maximum pitch and roll of 7 degrees and 14 degrees, respectively. In addition, the range variations of heave showed a standard deviation of 26 cm, along with the maximum value of 102 cm. They are also believed that the vessel was pitching, rolling and heaving more at the offshore area than when it was departing and approaching the harbor, as a smaller scale of variation was found from the values estimated from the GPS data collected at the beginning and ending of the session.

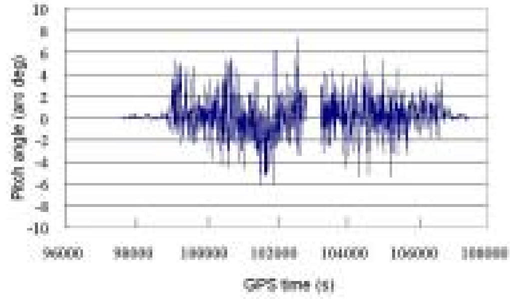

Fig. 11 Variations of pitch angle estimated from the field work

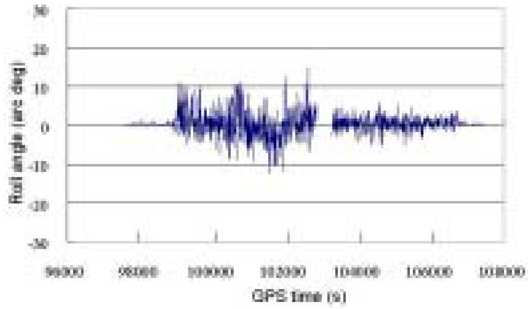

Fig. 12 Variations of roll angle estimated from the field work

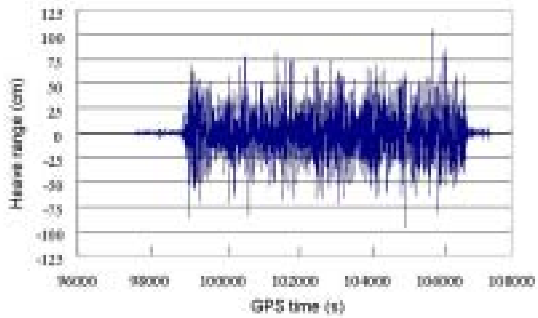

Fig. 13 Variations of heave range estimated from the field work

To estimate the precision of the GPS solutions for the data collected, the length variations of the antenna vectors were also investigated. This is based on a constrain that the baseline length between any two GPS antennas onboard the vessel is assumed to keep as fixed during the test. The length variations, differed from the average length, are now shown in Fig. 14 and Fig. 15 for the GPS antenna baseline I-II and I-III, respectively.

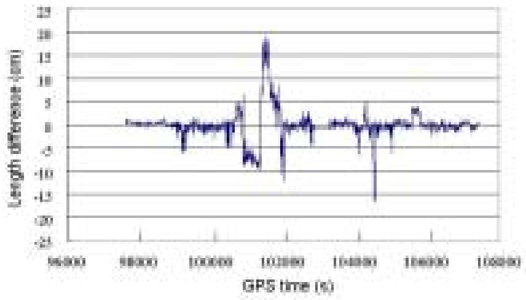

Fig. 14 Variations of length differences for the antenna vector I-II

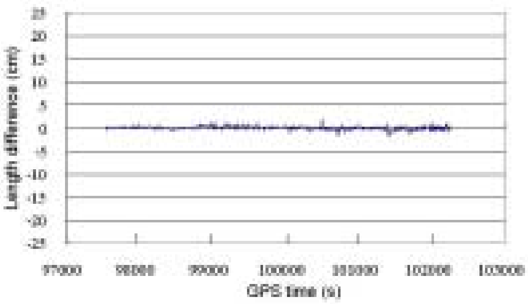

Fig. 15 Variations of length differences for the antenna vector I-III

It can be found from Fig. 14 that the baseline length differences varied more significantly when the vessel was driving away from the harbor with more influences from the sea state. However, this phenomenon was not shown in Fig. 15 as the GPS antenna III was fixed at stern more steadily by using a tribrach, compared to the antenna II using a higher pole to fix it at bow. In summary, the precision of the GPS solution estimated from the scatter values of the length differences for all the GPS antenna vectors showed an average standard deviation of 2.3 cm.

4.2 Bathymetric Rductions

The bathymetric reductions, based on using bathymetric data and attitude parameters estimated from carrier phase-based kinematic GPS solutions, were assessed in order to investigate 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 [10].

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 only seven check points were found from the field test data sets due to the time limitation of the field work. 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 results, based on using attitude-corrected and not corrected, are now summarized in Tab. 2 for effectiveness evaluation.

Tab. 2 Accuracy test for bathymetric measurements

assessment (unit)	not corrected	corrected with pitch and roll	corrected with heave	corrected with all parameters
min. abs. difference (cm)	16	14	2	8
max. abs. difference (cm)	81	68	76	78
avg. abs. difference (cm)	51	37	41	29
accuracy passing ratio	5/7	6/7	4/7	6/7
improvement	n/a	28%	20%	43%

The accuracy improvement shown in Tab. 2 is the percentage of average absolute differences obtained by the GPS-based technique, reduced relatively from those based on the bathymetric measurements not corrected with the attitude parameters. The accuracy satisfaction ratio is the number of successful check points over the total (7).

Referred to the values listed in Tab. 2, a higher level of measurement error is apparent in those not corrected with any attitude parameters. This basically reflects the importance of applying the attitude parameters of pitch, row and heave to the bathymetric reductions. As the GPS-based multi-antenna system is mainly expected to provide the attitude parameters for reductions, the accuracy improvement from the measurements not corrected with the attitude parameters to the attitude-corrected bathymetric measurement is estimated to be up to 22 cm or 43%, when a full set of attitude parameters was applied. The conclusion also drawn from Tab. 2 is that introducing a full set of attitude parameters for bathymetric reductions appears to provide most accurate and reliable bathymetric measurements than those of corrected with only angular parameters of pitch and roll, or vertical movement of heave.

5 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 attitude-corrected bathymetric measurements. The kinematic solutions of the onboard GPS antennas can effectively determine and provide the full set of attitude parameters, including roll, pitch and heave, for the reductions of bathymetric measurements to the vertical. The tilt error can then be reduced, and the accuracy of measurement can be significantly improved. The attitude correction, based on the kinematic GPS solutions from a multiple antenna configuration, has successfully shown its important role in bathymetric data reductions.

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