Article

Precise Tide-independent Bathymetric Survey and Application to the Inshore Monitoring of Seabed Evolution

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Abstracts

Due to the influences of tidal water level, vessel attitude and wave motion, the traditional bathymetric method of reducing depths by the tidal level makes it difficult to meet precise engineering requirements in the vertical direction. Therefore a precise method, termed a tide-independent bathymetric survey, is presented in this paper. In this method, the quality of the sounding and positioning solution, the influences of time offset and vessel attitude as well as height transformation are considered by taking a series of measurements. The tide-independent method has been used for inshore monitoring of the seabed sediments. The statistical parameters acquired by comparing the traditional method with the tide-independent method used in the monitoring show that the latter is accurate and credible.

Résumé

En raison de l'influence du niveau de la marée, de l'attitude du navire et du mouvement de l'eau, la méthode bathymétrique traditionnelle de réduction des profondeurs par le niveau de l'eau rend difficile la satisfaction d'exigences précises d'ingénierie dans la direction verticale. Cet article présente donc une méthode précise, appelée levé bathymétrique indépendant des marées. Dans cette méthode, la qualité du système de sondages et de détermination de la position, les influences des décalages temporels et l'attitude du navire ainsi que la transformation de la hauteur sont pris en compte dans une série de mesures. La méthode indépendante des marées a été utilisée pour le contrôle côtier des sédiments du fond de la mer. Les paramètres statistiques obtenus en comparant la méthode traditionnelle à la méthode indépendante des marées utilisée montre que cette dernière est exacte et crédible.

Resumen

Debido a las influencias del nivel del agua de las mareas, la actitud de los buques y el movimiento de las olas, el método batimétrico tradicional de reducción de profundidades mediante los niveles de las mareas dificulta el cumplimiento de los requerimientos precisos de ingeniería en la dirección vertical. Así pues, en este artículo se presenta un método preciso, denominado levantamiento batimétrico independiente de las mareas. En este método, la calidad de los sondeos y la solución del posicionamiento, las influencias del desfase horario y de la actitud de la nave, así como la transformación de las altura son consideradas mediante la toma de una serie de mediciones. El método independiente de las mareas ha sido utilizado para el control costero de los sedimentos del fondo del mar. Los parámetros estadísticos adquiridos comparando el método tradicional con el método independiente de las mareas utilizado en el control muestran que este último es exacto y creíble.

Regarding the traditional bathymetric measurement, the accuracy of the derived depth is limited by the tidal model, the vessel attitude and other factors, and it is difficult to satisfy the precise underwater engineering requirement (Zhao, J etc. 2004). The GPS RTK technique, which is applied widely in hydrographic surveying, can achieve centimetre-level accuracy in horizontal and vertical directions under a kinematic situation. A type of tide-independent bathymetric measurement has now been developed in China as an alternative to the traditional method. This method depends on the GPS providing a horizontal solution to the location of the surveying point and a vertical solution for the determination of the instantaneous height of the transducer, while ignoring the influences of vessel attitude and the systematic time offset for positioning and sounding. At the same time the GPS RTK positioning quality is also not considered in this method. Although the simplified tide-independent bathymetric method improves working efficiency and simplifies the working procedure in actual application, its final accuracy still cannot meet the precise requirements of hydrographic engineering. In order to improve the above shortcomings, a precise method of tide-independent bathymetric measurement is examined and described in this paper.

Equipment Arrangement and Surveying

In order to achieve an accurate vertical and horizontal solution in hydrographic survey, two double-frequency GPS receivers are used to determine the instantaneous 3-dimension coordinates of the surveying point. One is used as the reference station; the other is used as a mobile on the vessel. The RTK technique is adopted in the GPS survey (see figure 1 and figure 2). An MRU (Motion Reference Unit) is set up near the centre of the vessel for monitoring changes of the vessel's attitude. A digital compass is also mounted in line with the vessel's keel for measuring the heading of the vessel.

Before applying these sensors in practice, the lever arms of each of the sensors in the vessel frame system (VFS) needs to be measured (see figure 2). The definition of VFS is depicted on figure 7.Three sets of lever arms in the VFS are required in the data processing, which respectively is the phase centre of the mobile GPS antenna, the centre of the transducer surface and the centre of the MRU. In addition, we also need the height difference between the GPS antenna and the water surface for estimating the instantaneous tidal water level by GPS height and checking the credibility of the GPS measurement, and the difference between the GPS-antenna and the echosounder for acquiring the accurate depth of the surveyed sea bottom.

In addition, these sensors also need to be adjusted before measurement. A set of parameters used for transforming WGS84 coordinates to local coordinates are calculated with the data of a GPS control network which covers the water area of interest. The initial installation biases of MRU in roll, pitch and heave direction are acquired by statistically analys-

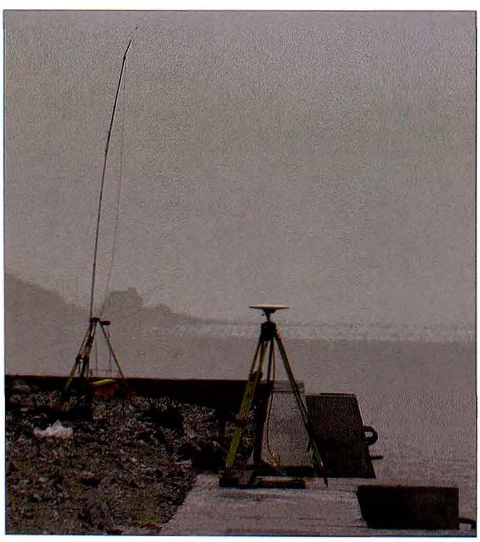

Figure 1: RTK reference station.

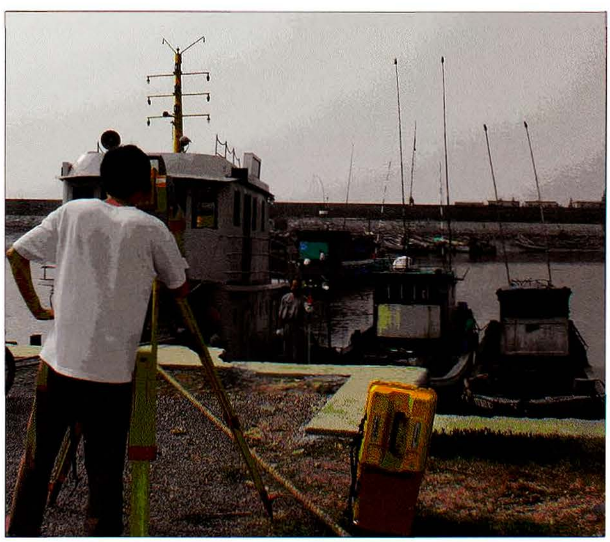

Figure 2: Measuring lever arms of sensors on VFS.

ing a time series of roll, pitch and heave measured in harbour under relatively peaceful sea conditions. We also adjust the digital compass with a 20,5,5,5 alignment. The digital compass is aligned to an accurately known absolute position. The alignment sequence being 20 minutes static on one heading and then 5 minutes static on a heading 90 degrees from the original heading. The unit was then rotated a further 90 degrees and remained static for a further 5 minutes and this step was repeated one more time. The above procedures provide a probability of achieving a higher accuracy using tide-independent bathymetric measurement.

Methods in Data Processing

Quality Control

Two essential factors will determine the final accuracy in this precise tide-independent method. One is the quality of sounding data; the other is the GPS solution. Therefore it is very important to implement quality control for these two factors.

Sounding Edit

Due to changes in vessel velocity, complicated seabed topography, as well as fish or seaweed in the water column, the bottom echo often suffers from bottom detection failure which might leads to abnormal sounding and a misinterpretation of the seabed topography. Generally, seabed variation is gradual and slow. Thereby we can diagnose and edit sounding data from a continuous echogram (see figure 3).

Filtering of GPS Positioning Data

In tide-independent bathymetric measurement, GPS has an important role in not only providing the positioning and navigation service, but also providing an instantaneous vertical datum to the surface of the transducer instead of that provided by a tidal model. This is why we call the method in this paper tide-independent bathymetric survey. Depth is relative and varies with the tidal level. Only when it is provided as an instantaneous height with respect to a vertical reference datum, can we express fixed seabed topography. For this reason, quality of the GPS height should be strictly controlled during data processing in this method.

Due to the integrated influences of rough sea situation and other factors, GPS positioning quality sometimes becomes poor and may even fails. Therefore two measurements are taken in filtering the GPS height solution. One is used for the modification of short-time interruption or abnormity in GPS height records, which is called heave modification, while the other is used for the modification of long-term abnormal records, which is named integrated modification of heave and tidal level.

The GPS and the MRU monitor the same vertical motion of vessel, thus heave can be used as a reference to check and amend GPS height. The consistency between GPS height and heave is presented in figure 4, and heave modification is also depicted in the figure.

Raw GPS height series with abnormal records that are marked with red circles, heave series and corrected GPS height series by heave modification are shown respectively in (a), (b) and (c).

Since on-the-fly GPS tidal level can be substituted for traditional tidal level in inshore hydrographic surveying (Jianhu Zhao, 2004), we can integrate GPS tidal level $h_{GPS\text{-}tide}$, heave dh_{heave} and transducer draft dh_{draft} to produce an instantaneous height h_T at the transducer surface.

$$h_T = h_{GPS\text{-}tide} - dh_{draft} + dh_{heave} \tag{1}$$

Where, $h_{GPS\text{-}tide}$ and dh_{heave} reflect long-period and short-period vertical motions of vessel respectively.

By means of attitude correction, we can correct height at the GPS antenna to that (h_G) at the transducer

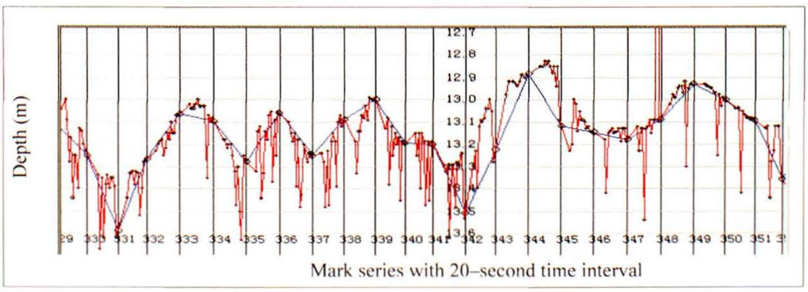

Figure 3: Sounding edit. Red line is echogram with 1-second surveying rate. Blue line denotes actual samples with 20-second sampling rate.

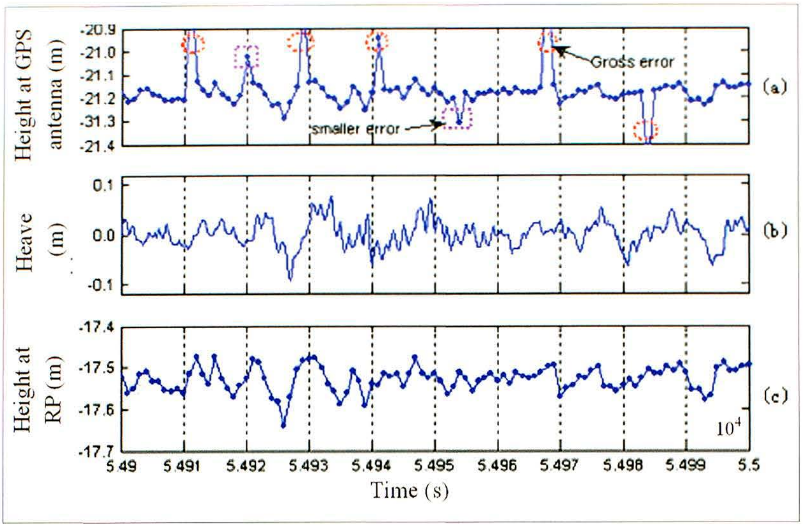

Figure 4: Heave modification.

we basically fulfill synchronized data logging from GPS receiver and echosounder, there still exists time offset between the two sensors due to the GPS RTK working model, which leads to a mismatch between the positioning solution and the sounding solution and an inconsistency in to-and-fro sounding profiles (see figure 6).

Time offset has a significant influence upon precise hydrographic surveying, which can reach 0.9 second at most. Therefore it is very necessary to detect and correct it. For the system applied to the water area in which the depth change is not obvious, time offset can be considered as a constant according to our research. Time offset can be de-

surface with the lever arm of the GPS antenna and attitude parameters. Referring to h_T, we can check and modify h_G, the integrated modification of heave and tidal level is depicted in figure 5.

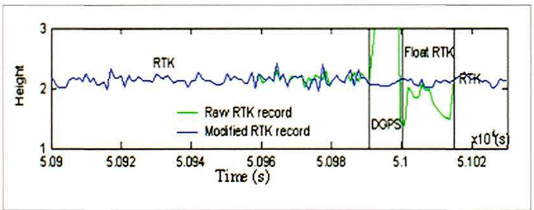

Figure 5: The integrated modification with GPS tidal level and heave. The green line reflects raw GPS height series, while the blue reflects amended one.

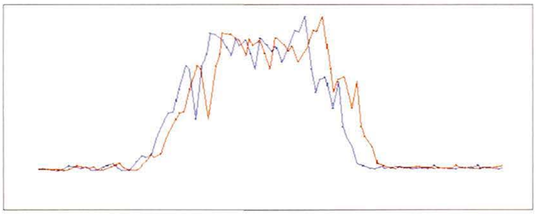

Figure 6: An inconsistency between to-and-fro sounding profiles resulted from time offset. In the figure, the blue and red lines represent two-way profiles respectively.

No matter how heave modification or integrated modification is carried out, height at the GPS antenna and referenced series such as heave, should be corrected to the same point in the VFS by attitude correction. While, after the modification at the point, corrected GPS height should also be corrected back to the GPS antenna by a reversing attitude correction. Filtering of the GPS horizontal solution is implemented by Kalman filter, in which heading derived from the digital compass plays an auxiliary role.

Correction of Time Delay

It is very important to ensure synchronization between the GPS positioning and sounding. Although

termined in two ways. One is to calculate it by comparing the coordinates and time of characteristic point pairs in to-and-fro profiles; the other is to get it according to a comparison of to-and-fro profiles. If the distance between a pair of characteristic points or the displacement at maximum comparison of to-and-fro profiles is ds, and mean velocities are v_1 and v_2 in corresponding profile measurement, then, the time offset, dt, is

$$dt = ds/(v_1 + v_2) \tag{2}$$

Then we can implement the correction of time offset and make sounding and positioning match. If a point's coordinates are x', y' and h', its actual coordinates (x, y, h) is modified as:

$$x = x' + ds\cos A \quad y = y' + ds\sin A$$
$$h = h' + (dh_{heave-2} - dh_{heave-1}) \quad ds = vdt \tag{3}$$

Where, v is mean vessel velocity; A is orientation angle derived from digital compass; $dh_{heave-1}$ and $dh_{heave-2}$ are heave parameters at t and $(t + dt)$ respectively.

Attitude Correction

Vessel attitude changes with wind, wave and vessel operation, which makes the positioning and sounding reflect 3-dimension coordinates and depth at different points rather than at the same point. In order to match the positioning and the sounding at the same point, we should implement attitude correction.

If the vessel's coordinate system (VFS) is defined as in figure 7, the lever arm of GPS antenna in VFS is (DX_G, DY_G, Dh_G) and that of sounding point is (DX_p, DY_p, Dh_p), then attitude correction can be implemented with attitude parameter roll (r) and pitch (p) by the following procedure.
Firstly, calculate instantaneous coordinates $(DX_{G\text{-}VFS}, DY_{G\text{-}VFS}, Dh_{G\text{-}VFS})$ of GPS antenna and that $(DX_{P\text{-}VFS}, DY_{P\text{-}VFS}, Dh_{P\text{-}VFS})$ of sounding point in VFS using formula (4) and (5) respectively.

$$\begin{pmatrix} dX_{G-VFS} \\ dY_{G-VFS} \\ dh_{G-VFS} \end{pmatrix} = R_p R_r \begin{pmatrix} dX_G \\ dY_G \\ dh_G \end{pmatrix} = \begin{pmatrix} \cos p & 0 & -\sin p \\ 0 & 1 & 0 \\ \sin p & 0 & \cos p \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos r & \sin r \\ 0 & \sin r & \cos r \end{pmatrix} \begin{pmatrix} dX_G \\ dY_G \\ dh_G \end{pmatrix} \tag{4}$$

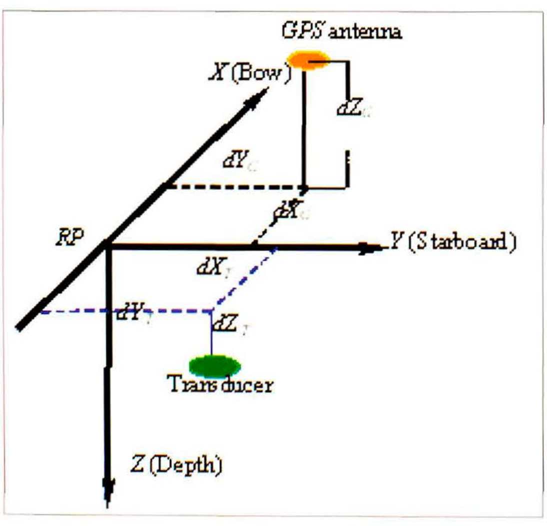

Figure 7: Vessel frame system (VFS).

$$\begin{pmatrix} dX_{p-VFS} \\ dY_{p-VFS} \\ dh_{p-VFS} \end{pmatrix} = R_p R_r \begin{pmatrix} dX_p \\ dY_p \\ dh_p \end{pmatrix} = R_p R_r \begin{pmatrix} dX_T \\ dY_T \\ dh_T + D - dh_{draft} \end{pmatrix} \tag{5}$$

where, R_p and R_r are matrixes constructed with r and p; (DX_T, DY_T, Dh_T) is the lever in the transducer in VFS; D and dh_{draft} represent depth and transducer draft respectively.

Then, transforming coordinates vectors in formula (4) and (5) from VFS to GRF (geographic reference frame) by formula (6), we can get coordinate increment of each sensor relative to RP (Reference Point, see figure 7) in GRF with R_h matrix constructed with heading parameter.

(6)

where, $(DX_{G\text{-}VFS}, DY_{G\text{-}VFS}, Dh_{G\text{-}VFS})$ and $(DX_{p\text{-}VFS}, DY_{p\text{-}VFS}, Dh_{p\text{-}VFS})$ are corresponding to $(DX_{G\text{-}GRF}, DY_{G\text{-}GRF}, Dh_{G\text{-}GRF})$ and $(DX_{p\text{-}GRF}, DY_{p\text{-}GRF}, Dh_{p\text{-}GRF})$ in GRF.
Finally, we acquire 3-dimension coordinates (Xp, Yp, hp) of sounding point in GRF.

$$\begin{aligned} X_p &= X_G - dX_{G\text{-}GRF} + dX_{p\text{-}GRF} \\ Y_p &= Y_G - dY_{G\text{-}GRF} + dY_{p\text{-}GRF} \\ h_p &= h_G + dh_{G\text{-}GRF} - dh_{p\text{-}GRF} \end{aligned} \tag{7}$$

Height transformation

Height derived from GPS is ellipsoidal height based on the WGS84 ellipsoid. While the height we often adopt in actual engineering is orthometric height/normal height based on geoid/quasi geoid, or chart height based on chart datum. The relations among these height systems and reference surfaces are depicted on figure 8.

Referring to figure 8, if we know geodetic height N / height abnormal ζ from a geoid model/quasi geoid model, then we can transfer ellipsoid height h to orthometric height H^o/normal height H^g by the formula (8) or (9).

$$H^o = h - N \tag{8}$$
$$H^g = h - z \tag{9}$$

If chart datum is defined according to tide and expressed with orthometric height or normal height, then we can draw the relation between chart datum and geoid or quasi geoid at each of the tidal gauges.

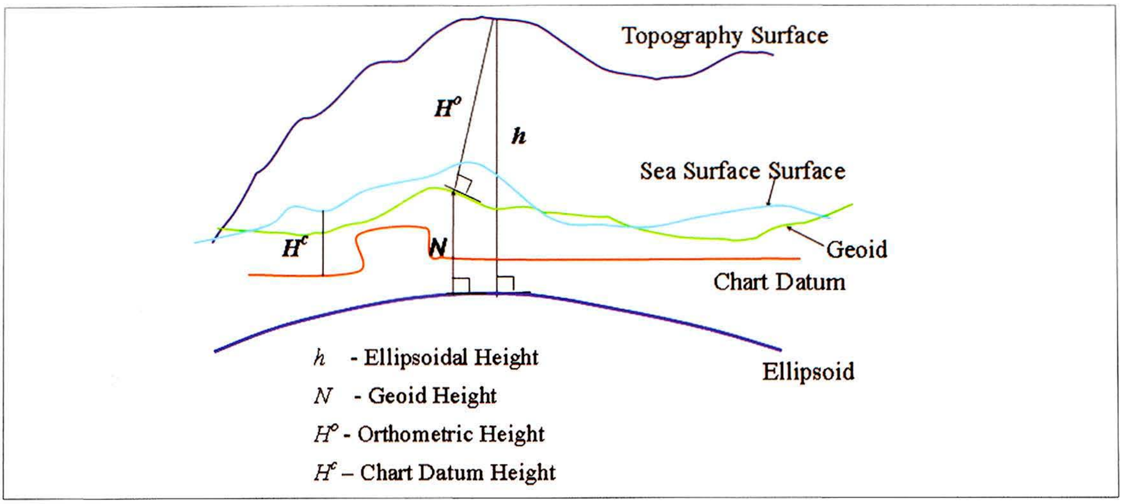

Figure 8: Height systems and the relationships among them.

Sensor	X /m	Y /m	H /m	Δh /m	Δr /°	Δp /°	Δ_{draft} /m
GPS Antenna	3.910	1.290	-1.235	/	/	/	
Transducer	3.910	1.290	3.130	/	/	/	0.65
TSS DMS-10	0.000	0.000	0.000	0.000	1.851	3.946	

Table 1: Lever arms in VFS and initial parameters of sensors.

We call it chart datum height dN. Using dNs at different tidal gauges, a model reflecting the relation between the vertical reference datum surfaces can be constructed as $dN(x, y)$, which is the function of location (x, y). Now H^o or H^g can be transformed to chart height H^C.

$$H^C = H^O - dN(x,y) \tag{10}$$

Of course, if we can get the separation between ellipsoid surface and chart datum, the transformation can be finished directly.

Applications and Analysis

The above method was applied to precise monitoring of sediments in the sea area of Xiangshan, China, covering an area of 2.5 kilometres length and 1.5 kilometres width. A positioning accuracy of higher than 10 centimetres was required in this project. In order to meet with the accuracy, two Trimble R7 GPS receivers and the GPS RTK technique were used in the monitoring. A TSS DMS-10 heave meter was mounted near the gravity centre of the vessel for monitoring vessel attitude, and an HMR3000 compass was aligned parallel to the keel of the vessel for monitoring the heading of the vessel in real time. Lever arms of these sensors in the VFS were measured with total station, which is shown in table 1. In addition, tidal gauge 1 and tidal gauge 2 were set at Liuheng island and Duizhi hill for testing the accuracy of the precise tide-independend method (see figure 9).

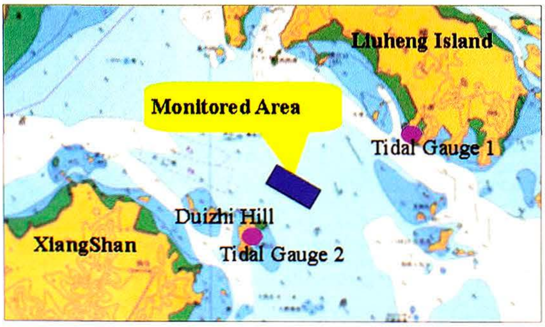

Figure 9: location of the monitored area and distribution of the two gauges.

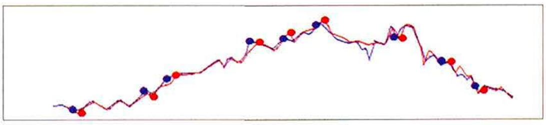

Figure 10: Determination of the time offset.

Time offset is determined by comparing characteristic points' pairs, which is shown in figure 10. In the figure, a pair of characteristic points is expressed as a red ball and a blue ball. Distance between the point pair is calculated with their horizontal coordinates. Integrating with velocity in to-and-fro profile's measurement, we acquired 0.65 second of mean time delay with 4.8 centimetres accuracy in depth.

In actual surveying, we designed and measured 22 transect lines and 4 check lines. Sampling rates of GPS RTK, transducer, TSS DMS and HMR3000 are set as 1Hz, 10Hz, 20Hz and 20Hz respectively. Event mark was triggered at each of four metres along the surveying line. Hypack software is used for data logging. The vessel maintained an average velocity of 7-knots during the surveying period.

In the data processing, the first work was the correction of time delay. The work is implemented with 0.65-second time delay, vessel course derived from HMR3000 compass and vessel velocity derived from GPS by formula (3). If the vessel sailed along the surveying line strictly at an average velocity of 7-knots in the project, the time delay brought about 2.3-metre distance offset between the logging position and the actual position. The distance offset is considered in the tide-independent method but ignored in the traditional method. Then the raw positioning solution was corrected and synchronized with the sounding data. At the same time, the correction also fulfilled the synchronization between positioning and heave, which is very helpful to heave modification.

The second work is quality control of raw sounding and positioning data. In this work, sounding edit is implemented by referring to the continuous sounding echogram. Some abnormal sounding records are modified or deleted. And at the same time, some sounding points are added in some characteristic terrain to enhance sounding presentation. RTK positioning horizontal solution is filtered by integrating Kalman filter with compass modification. RTK vertical solution is checked and modified by integrating heave with tidal level.

After acquiring high-quality and synchronous data of sounding and positioning, the third step is attitude correction. Attitude correction was implemented with lever arms shown in table 1, attitude data, pos-

Attitude				Coordinates correction		
Heave /m	*Roll /°*	*Pitch /°*	*Head /°*	*Dx /m*	*Dy /m*	*Dz /cm*
-0.032	1.448	-0.227	46.874	0.703	0.144	2.0
-0.097	2.622	-0.294	46.772	0.542	0.565	1.7
0.024	-2.270	-0.290	47.485	1.289	-1.210	-6.0
0.130	-1.897	-0.170	48.615	1.226	-1.090	-4.6
-0.043	2.783	-0.193	49.064	0.546	0.605	1.5
-0.042	1.844	-0.257	49.974	0.647	0.287	2.0
0.020	-0.543	-0.253	49.820	0.999	-0.600	-0.6
-0.020	-1.836	-0.196	50.411	1.170	-1.107	-4.4
0.004	-2.038	-0.143	52.700	1.182	-1.199	-5.1
0.006	-2.102	-0.130	52.900	1.153	-1.259	-5.4
-0.001	-1.149	-0.207	52.595	1.057	-0.869	-2.2
-0.086	-0.022	-0.227	51.780	0.889	-0.471	0.5
-0.129	0.930	-0.247	51.355	0.774	-0.119	1.7
-0.020	-1.630	-0.250	51.188	1.119	-1.065	-3.7
0.028	-1.087	-0.240	50.071	1.076	-0.811	-2.0
-0.032	1.448	-0.227	46.874	0.703	0.144	2.0
-0.097	2.622	-0.294	46.772	0.542	0.565	1.7
0.024	-2.270	-0.290	47.485	1.289	-1.210	-6.0
0.130	-1.897	-0.17	48.615	1.226	-1.090	-4.6

Table 2: Attitude influence on 3 dimensions of a sounding point.

itioning solution and sounding solution by formula (4) to formula (7). Attitude can bring the obvious influences to 3 dimensions of sounding point. Using a part of survey data, we can calculate the influence of vessel attitude on horizontal (x, y) and vertical (z) of sounding point and show these in table 2. In the table, we can find that the maximum effects reached 1.289 metres in latitude direction, 1.259 metres in longitude direction and 6 centimetres in vertical direction (see table 2). However, these obvious influences are not considered in the tide-depended method.

Method	Mean dh/cm	Maximum dh/cm	Minimum dh/cm	Standard deviation /cm
Tide-independent (the new method)	0.5	9.6	-0.1	4.9
Tide-dependent (traditional method)	3.8	-47.2	0.8	15.8

Table 3: statistic parameter of height difference at each of point pairs.

Although we acquired the 3-dimensions of the sounding point by attitude correction, the height of the sounding point calculated by the above data processing is not what we want. We hope to express the underwater hydrography with chart height but not with the ellipsoid height from GPS finally. Thus it is necessary to find a transformation relation between vertical datum and fulfill height transformation in the project. Since the water area studied is small and close to a tidal gauge, we can build the relation between WGS84 ellipsoid height and 1985 National Height which is the normal height and based on the Chinese geoid. Similarly, we can obtain the relation between 1985 National Height and chart height which refers to the chart datum at the tide gauge. Using both of the two height transforming relations, the required height in the project is acquired at each of undersea points as a result. In order to analyze the accuracy of the tide-independed method and the advantage relative to the tide-depended method, sounding point pairs were found and compared at crossing points. Firstly, the 2-dimension coordinates 88 crossing point formed with 22 transect lines and 4 check lines are calculated according to each of the designated lines' equations (see figure 13). Secondly, the correspondingly 3-dimension coordinates of 88 point pairs can be extracted from the sounding data processed by the tide-independed method. Comparing each point pair in height, we can get a distribution of height difference, dh, at each of pairs, which are shown in figure 11 (a).

As a result of the tidal level, we can also acquire the distribution of height difference dh shown in figure 11(b) at each of the point pairs by traditional data processing method.

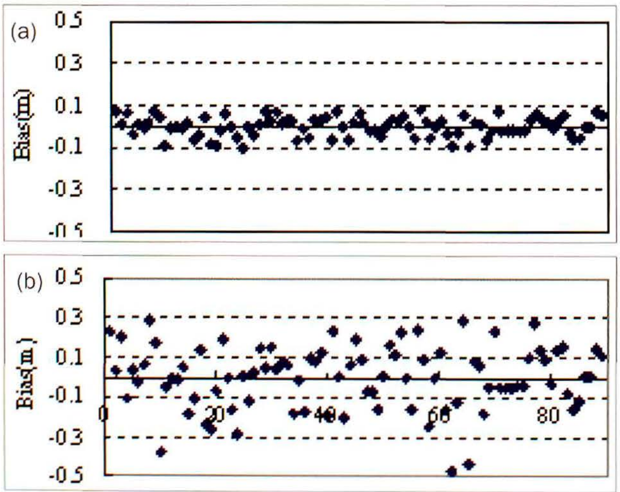

Figure 11: the distribution of height difference at each of the cross point pairs. The tide-independent method is used in (a), while the tide-dependent (traditional) method is used in (b).

Comparing and analyzing the distribution in figure 11, we found that the height difference is limited within 10 centimeters around mean of 0.5 centimeter in figure 11 (a), while within 50 centimeters around mean of 0.8 centimeter in figure 11 (b). Statistic analyses are used in the data in figure 11 (a) and 11 (b) respectively. The statistic parameters are shown in table 3.

Besides, the probability distributing of height difference dh in the tide-independed method and the tide-depended method at crossing point are calculated and shown in figure 12 (a) and (b).

The above statistical parameters in table 3, figure 11 and figure 12 illustrate clearly the precise tide-independent method has higher accuracy than the traditional method. The former increases the accuracy by a

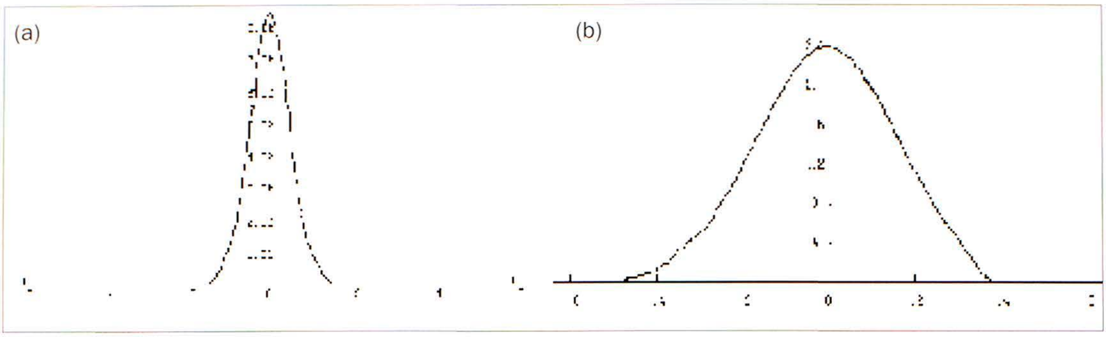

Figure 12: the probability distribution of height difference of crossing point pairs. The tide-independent method is used in (a), while the tide-dependent method is used in (b).

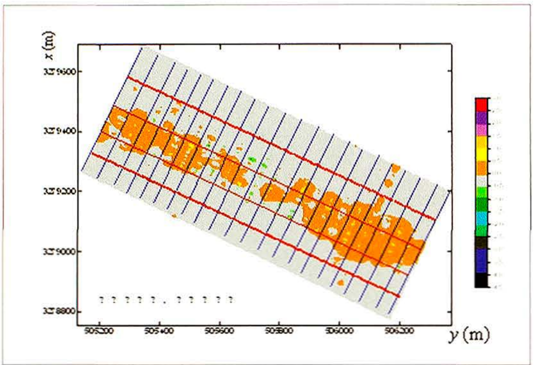

Figure 13: seabed evolution within 2 months in the monitored water area. The blue line denotes transect line and the red line denotes check line.

factor of three and has higher consistency of different measurements relative to the latter.

Monitoring changes of the seabed sediment needs to implement measurements many times according to the time period required in this project. Using the new method in each of monitoring measurements, a sediment evolution can be reflected with the processed result in any two measurements. After a two-month sediment evolution, the seabed change is shown in figure 13.

Conclusion

Compared with traditional methods, since each of the 3-dimensional solutions provided by GPS is independent and credible, the tide-independent method eliminates the systematic error in measurement and data processing. Besides, the tide-independent method determines the height of undersea point by integrating GPS height, lever arm of the GPS antenna in the VFS, vessel attitude, draft as well as sounding in data processing, thus it effectively overcomes the influences of tidal height and vessel attitude, and improves the final accuracy, especially in height. In addition to the above advantages, due to convenient implement in inshore engineering, the tide-independent method abolishes tidal observation and saves money.

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