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Determination of Precise Instantaneous Height at Multibeam Transducer

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Abstract To overcome the shortcomings of the traditional multibeam survey and data processing, a new method is presented for the precise determination of the instantaneous height at the multibeam transducer by the blend of GPS height and heave signals. Before signal blend, GPS height and heave signals need to be corrected first to the transducer center by attitude correction. Second, the GPS height needs to be checked and modified by heave check and modification itself. Butterworth and FFT (fast Fourier transformation) were used in the signal blend. Finally, FFT is thought to be appropriate in signal processing. The new method efficiently overcomes the shortcomings of the traditional method, and this is proven well by the MBS (multibeam bathymetric system) experiment.

Keywords multibeam; digital signal processing; GPS; heave
CLC number P228.42; P224; P223.7

Introduction

Two main error sources restrict the accuracies of multibeam results in the vertical direction. One is the accuracy of the instantaneous height at the transducer; the other is sounding accuracy (the vertical distance from the transducer to the seabed). For the latter, Duncan Mallace[1] systematically compared modern multibeam systems and thought that they basically satisfy IHO S44 Order-1 depth standard. Thus, this study will focus on the former.

In conventional multibeam sounding system (MSS) surveying, an estimate of the height at reference point (RP) can be acquired with tide, draft and heave. Apparently, the accuracies of the three influence the height accuracy. Due to acute vessel speed and heave algorithms, heave can only adequately capture vessel vertical motions with periods less than about 15 s[2]. Moreover, the accuracies of tidal observations and tidal models also restrict the accuracy. Besides, squat models do help to capture some of these variations due to long term speed changes; they are inadequate to cope with those rapid shifts experienced by survey vessels. The height at RP provided, with the three losses, a part of the signals and cannot completely reflect vessel vertical motion. Thus, the conventional method needs to be improved.

GPS carrier phase differential technique can achieve centimetre-level vertical solution under kinematic situation. The sampling interval of the GPS receiver can be set as 1 s at least in kinematic surveying, which can be used for observing vessel vertical motions with periods greater than 2 s. Thus, by virtue of the periodic ranges of GPS height and heave signal, it is possible to provide an entire period range signal with the both valid signals for the accurate presentation of actual vessel vertical motion.

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1 Acquisition of GPS height signal at RP

Time synchronization enhances the comparability of heave and GPS height in time scale and ensures the extraction of matching attitude parameters, while the comparability in magnitude change is represented in monitoring the vessel vertical motion at the same location such as RP. Suppose that instantaneous roll(r), pitch (p), and yaw changes the GPS antenna position in the vessel frame system (VFS). Thus, the correction needs a rotation matrix constructed with the attitude parameters and the initial lever arms (x, y, z) of GPS antenna in VFS. If we do not consider the yaw, the instantaneous location (x', y', z') of the GPS antenna in VFS can be expressed as the follows:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \boldsymbol{R}(r)\boldsymbol{R}(p)\begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{1}$$

Then, the height H_{rp} at RP is:

$$H_{\text{rp}} = H_{\text{GPS}} + z' \tag{2}$$

where H_{GPS} is the instantaneous height of GPS antenna.

2 Pre-processing of GPS height records

Although GPS carrier phase differential solutions have high statistical accuracy under ideal conditions, the actual instantaneous positioning quality may be degraded or become invalid due to a variety of factors. Thus, it is necessary to implement quality control for these original GPS height records.

2.1 Heave modification for short-time GPS abnormal

The good consistency of the GPS and heave signals shows that we can check and modify the former through the latter. However, because of the observing accuracy difference between the two signals, local distinction exists. Therefore, about ±11.2 cm bounds of ε should be adopted. The model can be represented as the following.

$$\delta_1 \leqslant 2\varepsilon, H_i^{\text{GPS}} \text{ is accepted}$$

$$\text{If}\quad \delta_1 > 2\varepsilon \ \ \& \ \ \delta_2 \leqslant 2 \ \text{ then } H_i^{\text{GPS}} = H_{i+1}^{\text{GPS}} + \Delta_{(i,i+1)}^{\text{heave}}$$

$$\delta_1 > 2\varepsilon \ \ \& \ \ \delta_2 > 2\varepsilon, H_i^{\text{GPS}} = ((H_{i-1}^{\text{GPS}} + \Delta_{(i,i-1)}^{\text{heave}}) + (H_{i+1}^{\text{GPS}} + \Delta_{(i,i+1)}^{\text{heave}}))/2 \tag{3}$$

where H_{i-1}^{GPS} (H_{i+1}^{GPS}) is reliable GPS height record at time i-1 (i+1), other symbols are explained as follows:

$$\delta_1 = \Delta_{(i,i-1)}^{\text{GPS}} - \Delta_{(i,i-1)}^{\text{heave}}, \delta_2 = \Delta_{(i,i+1)}^{\text{GPS}} - \Delta_{(i,i+1)}^{\text{heave}}$$

$$\Delta_{(i,i-1)}^{\text{GPS}} = H_i^{\text{GPS}} - H_{i-1}^{\text{RTK}}, \Delta_{(i,i+1)}^{\text{GPS}} = H_i^{\text{GPS}} - H_{i+1}^{\text{RTK}}$$

$$\Delta_{(i,i-1)}^{\text{heave}} = H_i^{\text{heave}} - H_{i-1}^{\text{heave}}, \Delta_{(i,i+1)}^{\text{heave}} = H_i^{\text{heave}} - H_{i+1}^{\text{heave}}$$

Several abnormities in the original GPS height series (Fig.1(a)) have been modified properly through the heave.

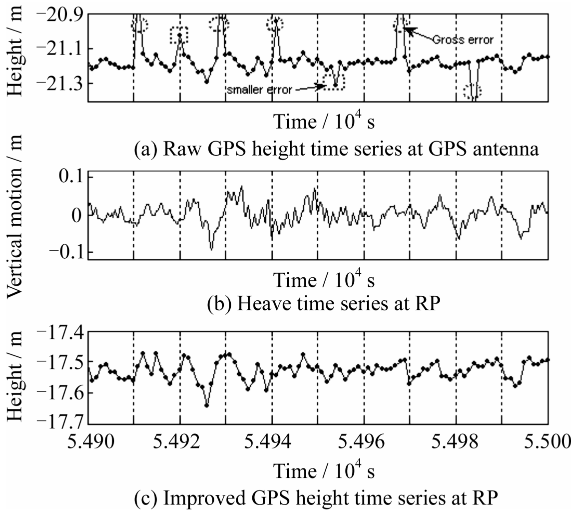

Fig.1 Heave modification and the relation between heave series and GPS series

2.2 Repair of continuously abnormal GPS height records

If some ill observation factors keep GPS surveying longer (few minutes), some continuous abnormal recorders will appear in RTK (real time kinematic) height time series when the enhancing mode is chosen in RTK observation, or a continuous interruption will be displayed due to PPK (post processing kinematic) quality control. These will result in the incorrect presentation of the instantaneous height at RP and pollute the final results.

If the same height datum is referenced in both the GPS positioning and the tidal observations, $H_{T\text{-rp}}$ and H_{rp} should be approximately equal. Thus, $H_{T\text{-rp}}$

can be considered for the modification of these continuous anomalies or interruption.

$$H_{T\text{-rp}} = H_T - \Delta h_{s\text{-draft}} + \Delta h_{d\text{-draft}} + \Delta h_{\text{heave}} \quad (4)$$

where $\Delta h_{s\text{-draft}}$ is $\Delta h_{d\text{-draft}}$ is static draft; Δh_{heave} is dynamic draft; Δh_{heave} is heave; H_T is tidal reading.

The above thought relies on exterior tidal readings. In the following, we will study the feasibility of directly using GPS height time series at RP to repair itself.

Considering the periodic characters of H_T, Δh_{draft} and Δh_{heave} in Eq.(4), and the relationship between $H_{T\text{-rp}}$ and H_{rp}, H_{rp} can also be constructed by the following formula.

$$H'_{\text{rp}} = H_{\text{lowfreq-rp}} - \Delta h_{d\text{-draft}} + \Delta h_{\text{highfreq-heave}} \quad (5)$$

where $H_{\text{lowfreq-rp}}$ is the low frequency H_{rp}; $\Delta h_{\text{highfreq-heave}}$ is high frequency heave.

Using Eq.(5), the continuous abnormal GPS records have been modified properly(Fig.2).

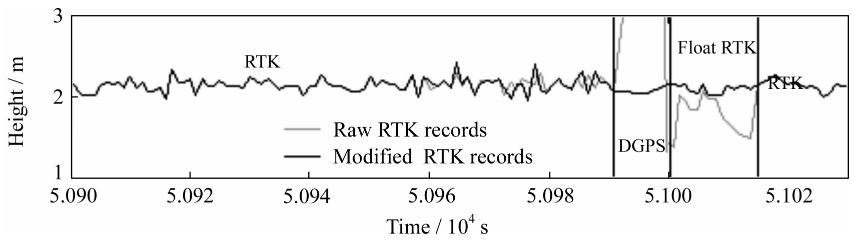

Fig.2 GPS height series modified by itself

3 Blend of RTK height signal and heave signal

GPS sampling interval can be set as 1 s, and can recover period signals more than 2 s. Clearly, the two signals have overlapping bandwidths and can be blended.

A high-pass filter and a low-pass filter are required in the above data processing in order to extract valid short-period signals $H_{\text{HF-heave}}$ from the heave and pick up medium/long-period signals $H_{\text{LF-GPS}}$ from the GPS height. Then, a new signal H_T can be acquired.

$$H_T = H_{\text{LF-GPS}} + H_{\text{HF-heave}} \quad (6)$$

To meet with the requirements of the signal blend in strictly matching phase and magnitude, FFT frequency spectrum processing will be adopted for designing the high-pass and low-pass filters in this study. The procedure is expressed in the following.

1) Use FFT to transform GPS signal and heave signal from time domain to frequency domain.

2) Give a proper cut-off frequency, picking up less than the cut-off frequency signals from the GPS height signals and more than the cut-off frequency signals from the heave signal.

3) Use inverse FFT to transform frequency domain signals to time domain signals. Then, we can acquire $H_{\text{HF-heave}}$ and $H_{\text{LF-GPS}}$ signals.

4) Through Eq.(6), a blended signal H_T can be acquired.

A cut-off period or frequency is required to extract valid signals. Through many experiments, we found that a 10 s cut-off period is proper.

Combining blended signals using Butterworth filter and FFT filter respectively (Fig.3 and Fig.4), it is easy to find that the latter is much better than the former.

4 Experiments and analysis

An experiment was implemented at the Mispec field of Bay of Fundy. Using the traditional method, the DTM of this region has been constructed (Fig.5).

We can clearly find alternating undulations in the two sides of the DTM. Zooming in the left side makes it more clear (Fig.6). Extracting the heave and GPS height series from one surveying line, it is easy to find that there are more undulations at the beginning of the heave series, and the biggest magnitude is up to 0.5 m, while the GPS height series is normal. This proves that the heave suffers easily from the abrupt changes of vessel velocity, and is difficult to represent in long periods unlike GPS height.

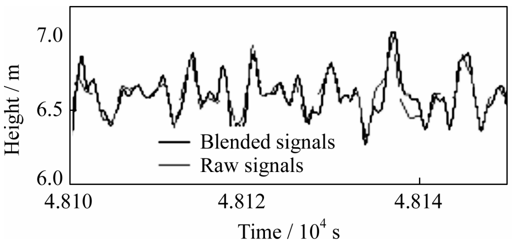

Fig.3 H_T blended by Butterworth filter

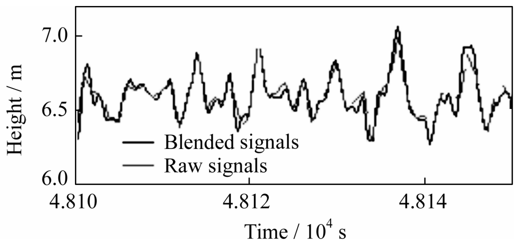

Fig.4 H_T blended by FFT filter

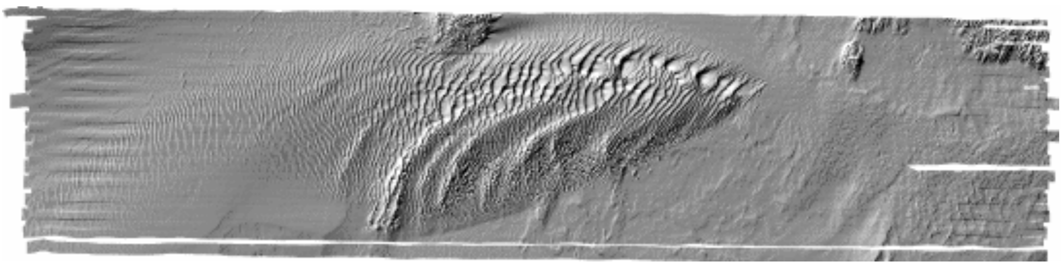

Fig.5 Seabed DTM constructed by traditional multibeam data processing method

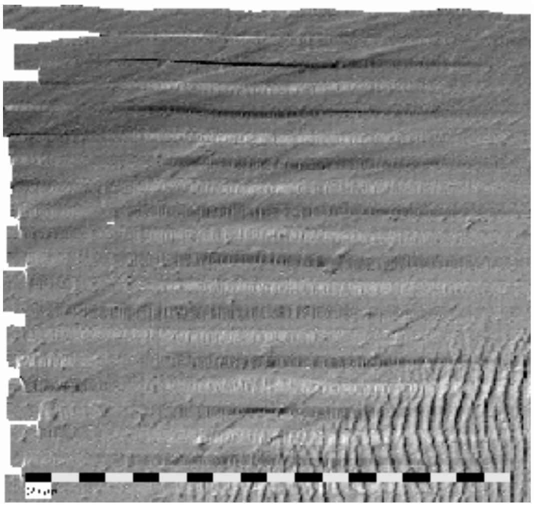

Fig.6 Zoomed in the left of the DTM in Fig.5

Two reasons can be used for explaining the problem. Firstly, the speedup and speed-down of vessel operation resulted in the abnormal heave changes in opposite directions at the beginning and end of the designing line when vessel came into and went away the line, and finally influenced the DTM. Secondly, the tidal level from the tidal gauge could not accurately reflect the actual tidal changes in the instantaneous position of the vessel due to tidal phase delay. Within a very short time, the influences could not be detected, however, a roundtrip surveying in the adjacent two designing lines might take a longer time (at least 45 min) and might bring more evident influences to the expression of both sides of the DTMs under the special tidal phenomenon (Fig.7).

GPS positioning is relative. Once a known coordinate is set at base station, the positioning solutions at the rover can be achieved with respect to the base station. Thus, the height at RP acquired by the signal

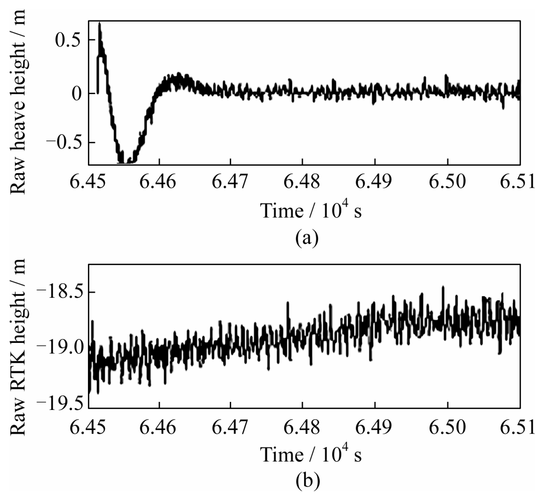

Fig.7 Mechanism analysis of abnormal DTM

blend is independent from the tidal changes at each epoch. A new DTM is constructed by the signal blend method and is shown in Fig.8. The new DTM removes the effect of the abnormal heave and reflects the seabed rightly.

In order to give an accuracy estimation of the signal blend method in a multibeam survey, a strict statistical analysis is done in the data processing of the Irving wharf experiment. Because each line was surveyed twice, using some data processing method (the conventional method or the signal blend method), we can construct two DTMs along opposite cruising directions at each line. Comparing the two DTMs, we can also calculate a statistical result of the difference of the two DTMs at each line, which reflect the interior

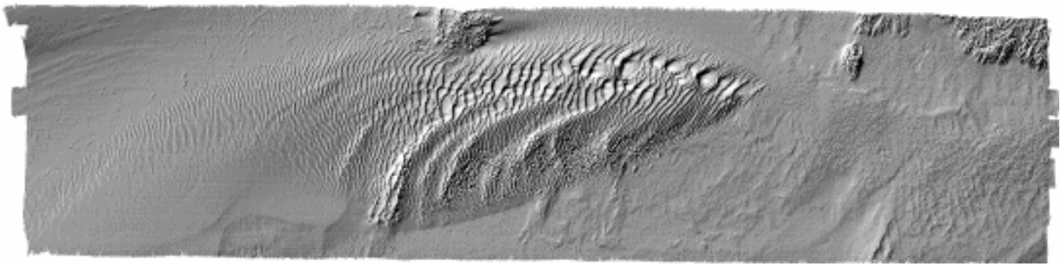

Fig.8 Seabed DTM reconstructed by signal blend technique

consistency of the method.

Comparing the seabed datum acquired by the traditional method and by the signal blend method with that under ideal condition and analyzing the former, the biggest deviation in the vertical direction is 14.1 cm and the least is −3.8 cm; the average deviation is 0.7 cm and the standard deviation is ±12.4 cm. While analyzing the latter, the biggest deviation in the vertical direction is 7.1 cm and the least is −2.8 cm; the average deviation is 0.1 cm and the standard deviation is ±4.7 cm. These statistical results show that the signal blend method is right and is much better.

5 Conclusions

1) The blend of GPS height and heave provides an entire frequency band signal at RP, efficiently overcomes the influence of abnormal heave, and faithfully reflects the actual instantaneous vertical motion at RP in the form of absolute height. Thus, it is better than the conventional method and can be used for precise multibeam surveying.

2) Considering that the accuracy of GPS positioning is influenced by the distance, the above method is adapted to the inshore precise multibeam surveying at present.

3) In order to achieve continuous and accurate GPS height solution, GPS RTK is recommended in wider area surveying, while PPK is better during complex area surveying.

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