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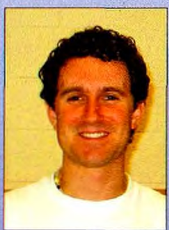

On the Fly GPS Tide Measurement along the Saint John River

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Abstract

Conventional tide measurement gives a separate reading at each tide gauge but cannot meet completely with the requirement of precise hydrographic survey for points between tide gauges. The GPS differential technique provides an alternative method for obtaining on-the-fly tides, which can only be achieved by applying latency correction, attitude correction, height transformation, draft correction and finally a data filter.

Résumé

Le mesurage des marées traditionnel permet d'obtenir une lecture séparée à chaque marégraphe mais ne peut pas répondre entièrement aux exigences de levés hydrographiques précis pour les points situés entre les marégraphes. La technique du GPS différentiel fournit une autre méthode d'obtention des marées à la volée qui ne peut être réalisée qu'en appliquant la correction du temps d'attente, la correction de l'attitude, la transformation des hauteurs, la correction du tirant d'eau et enfin un filtre de données.

Resumen

La medición convencional de marea proporciona una lectura separada en cada mareógrafo pero no puede cumplir totalmente el requerimiento de los levantamientos hidrográficos precisos para los puntos que se encuentran entre los mareógrafos. La técnica de GPS diferencial proporciona un método alternativo para la obtención de mareas "al sobrevuelo", que puede ser llevado a cabo únicamente aplicando la corrección de latencia, la corrección de actitudes, la transformación de alturas, la corrección de calado y, finalmente, un filtro de datos.

Introduction

The Ocean Mapping Group (OMG), University of New Brunswick, implemented a Hydrographic campaign along the Saint John River in the summer 2004. In the campaign, tide measurement was carried out in Long Reach (Figure 1), a fjord on the Saint John River.

The Saint John River flows from its headwaters in the state of Maine,USA, through Fredericton, and into the Bay of Fundy where the largest tide in the world occurs. The special tidal phenomenon unavoidably influences the tidal regime of the Saint John River, especially in that part of the river near Long Reach. In order to monitor the tidal variation, three tide gauges have been installed at Oak Pt, Beulah Camp and Days Landing in Long Reach (Figure 1). A 1.5-hour phase shift over 24 hours (Figure 2, upper) and 15-minute phase delay between adjacent tide gauges (Figure 2, lower) were detected. These imply a complicated interaction pattern between the river current and the influx of water from the Bay of Fundy. In order to efficiently monitor the water level changes, we need to either install more tide gauges or find other ways to obtain the tidal level at any position in the area.

Tidal level plays a very important role in providing a vertical reference surface for hydrographic surveys. Conventional tide measurement gives a separate reading at each tide gauge but cannot meet completely with the requirement of precise hydrographic survey for points between tide gauges (C.C. Chang 2002). It is necessary to seek a new method for obtaining the on-the-fly tides.

The GPS carrier phase differential technique has been used in many different engineering applications. Decimetre-level, even centimetre-level, accuracy in the vertical direction can meet with the requirement of a dynamic survey (Cary Wong, 2000; Paul Denys, 2002; C.C. Chang 2002; Rapatz, 1991). Thus the high continuity and credibility of GPS carrier phase differential technique makes possible a new method of tide measurement. In order to observe the actual tidal change in any position of Long Reach, on-the-fly GPS tide measurement is studied in this paper. Also, the methods and procedures of GPS tidal level data processing are presented.

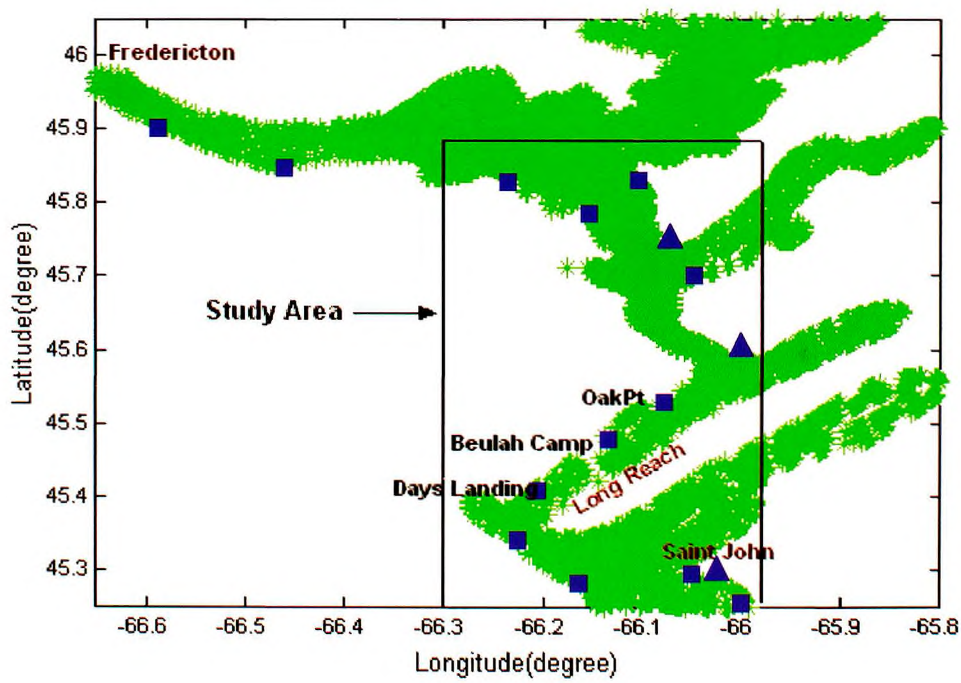

Figure 1: Saint John River and the distribution of tide gauges. ■: tide station (GPS/ levelling point); ▲: A-level GPS control point.

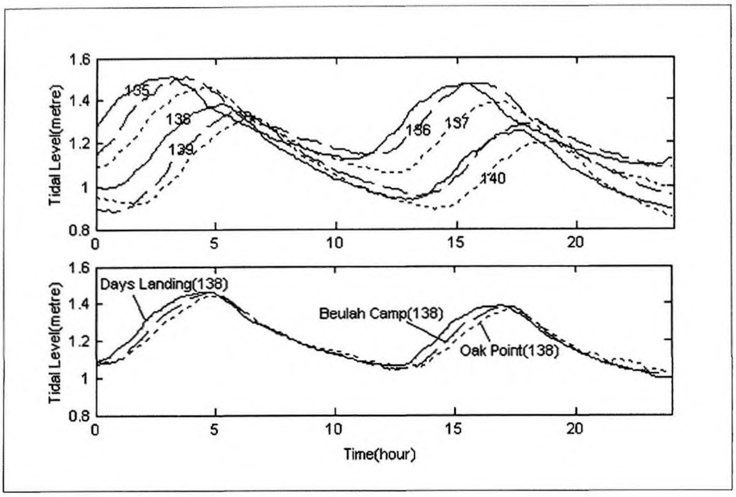

Figure 2: (a) Six-days' (Julian Day 135 to 140) tidal level data at Days Landing. (b) The three tidal readings observed at Days Landing, Beulah Camp and Oak Point on May 17, 2004 (Julian Day 138).

GPS Tide Observation

The C.S.L. *HERON* is a 10m survey launch operated by OMG on which a Simrad EM3000 Multibeam system and other acoustic and oceanographic instruments are installed. This launch was used to implement the GPS tide measurement on 17/18 May 2004. In the surveying, three Trimble GPS 5700 receivers are used. One is used as a base station, while the other two act as rover stations on board.

Considering the varying topography along the river and the radio radiation distance, two kinds of GPS carrier phase differential techniques were used in the GPS tide measurement. One is RTK (Real Time Kinematic); the other is PPK (Post Processing Kinematic). Base station data provides real time differential correction information for the RTK rover station. At the same time, raw base station data is also used for post processing with the PPK rover station data. The PPK and RTK rover stations are respectively set up at bow and stern of *HERON* (Figure 3).

In order to accurately calculate tidal level, the lever arms between the GPS antenna phase centres and the RP (Reference Point defined at the EM3000 transducer centre) are measured. The PPK antenna phase centre is located at (-0.39m, 0.01m, -4.07m)

Figure 3: The locations of the two GPS rover antennae on the HERON.

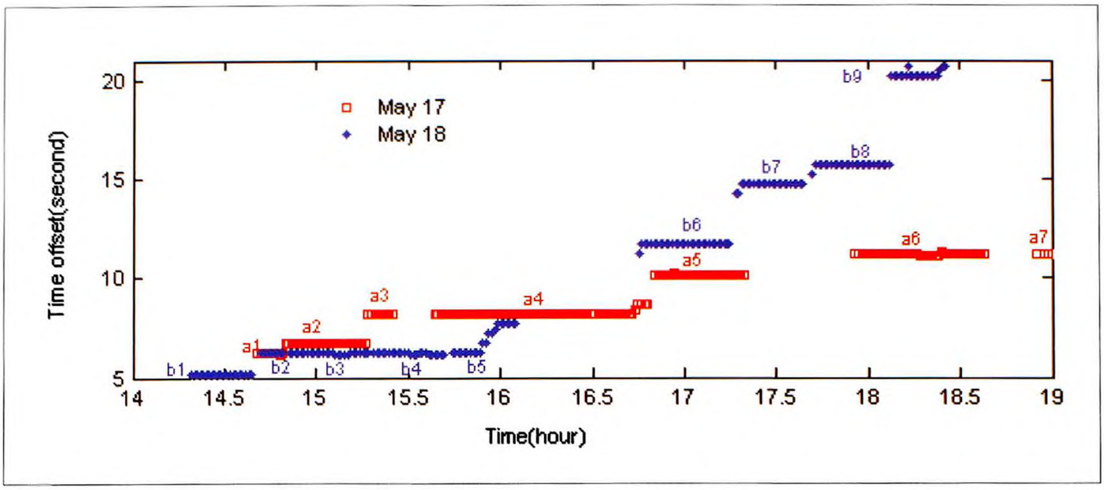

Figure 4: Time stamp the difference between Simrad clock and GPS time. The determination of time offset is based on the observation data of each survey line. If there is very small pause between adjacent survey lines, the time offset will be determined continuously in the figure. Otherwise, longer time interrupt will be found in the figure.

with respect to the RP in the Vessel Frame System (VFS). The location of the RTK rover antenna phase centre is (-4.77m, -0.41m, -3.83m) in the VFS.

A sampling frequency of 1 Hz, which is far less than the shortest tidal period and enables GPS observations to capture the entire frequency band of the instantaneous water surface, is set for each GPS receiver. In order to calculate a credible initialisation integer ambiguity in PPK data processing, about 10 to 15 minutes static observation was done at the beginning and end of the GPS tide measurement.

In addition to the GPS measurements, the tidal level is also read with 15-minute sampling interval at Oak Point tide gauge and with 5-minute sampling interval at Beulah Camp and Days Landing tide gauges.

GPS Tidal Level Data Processing

Vessel motion changes the location of GPS antenna relative to RP in VFS, which leads to incorrect instantaneous water surface determined directly with raw GPS vertical solution. Thus, it is necessary to first eliminate the effect of vessel attitude and transfer the height at the GPS antenna to the height at RP. Draft correction shifts the height from RP to water surface. Because the water surface is unstable, we need a low-pass filter to remove the high-frequency noise and extract valid tidal level from it. For the actual applications, a height transformation from ellipsoid height to chart height should also be required in the data processing.

Correction of Time Delay

As an essential requirement of multibeam surveys, the attitude parameters are logged from MRU (Motion Reference Unit) and marked by the Simrad EM3000 system time, while GPS sampling is marked by GPS UTC time. The problems of initial time synchronisation and the drifts of the two clocks result in a mismatch between Simrad time and UTC time. An evident and irregular variation can be found in a long time delay series (Figure 4). In order to extract exactly attitude parameters and match GPS height solution, this time delay needs to be detected and compensated.

During multibeam surveys, GPS positioning data is continuously logged into the Simrad EM3000 system and marked by the system time. A navigation (NAV) file is produced in the procedure. At the same time, the original GPS NMEA-1083 information is also saved in a separate NMEA file in the system. This means that the same positioning information is marked twice with Simrad time and UTC time. Thus, the time offset can be found easily by comparing the two time series that are extracted from the NAV file and the NMEA file.

Attitude Correction

After ensuring the synchronisation of the GPS UTC clock and Simrad clock, matching attitude parameters can be extracted and used for attitude correction.

In attitude correction, we need to define a Vessel Frame System (VFS) as shown in Figure 5. The ori-

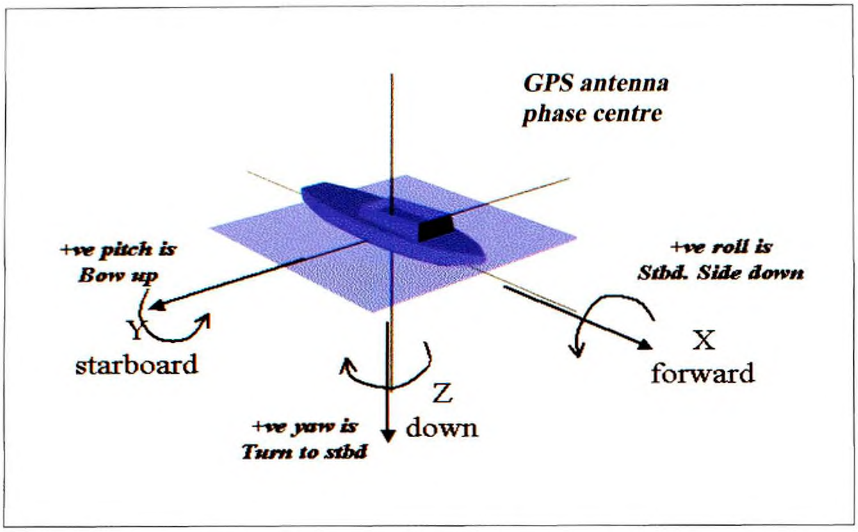

Figure 5: The definitions of Vessel Frame System and attitude parameters.

gin of VFS is defined at the EM3000 transducer centre (RP). The X axis is parallel to the centre line of vessel and points forward; the Y axis is perpendicular to X axis in plane and points to starboard. The Z axis is perpendicular to the XY plane and points downwards. VFS is a right hand perpendicular coordinate system. In the coordinate system, the roll, pitch and heading rotations are defined on the following figure.

Under an ideal situation (both roll angle (r) and pitch angle (p) are zero), if the coordinate of GPS antenna phase centre in the VFS is (x, y, z), in the general situation, the instantaneous coordinate (x', y', z') of GPS antenna phase centre can be expressed as the following.

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = R_r R_p \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos r & \sin r \\ 0 & -\sin r & \cos r \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos p & \sin p \\ 0 & -\sin p & \cos p \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (1)$$

Then, the ellipsoid height H_{rp} of RP is:

$$H_{rp} = H_{GPS} + z' \quad (2)$$

Where, H_{GPS} is the instantaneous ellipsoid height of GPS antenna phase centre.

Height Transformation

The height derived from GPS is ellipsoidal height, while orthometric height or chart height is normally adopted in tide measurements and hydrographic survey (B.Erol, 2003). Thus two transformations are required in GPS tide data processing. One is from ellipsoidal height to orthometric height; the other is from orthometric height to chart height. For the first transformation, ellipsoid/geoid separation N is required.

$$H^o_{rp} = H_{rp} - N \quad (3)$$

Where, H^o_{rp} and H_{rp} are respectively the orthometric height and ellipsoidal height at RP.

The ellipsoid/geoid separation N can be obtained by a physical or geometric geoid model (B.Erol, 2003). Two Canadian national geoid models (GSD95, CGG2000) can provide the separation N in the river segment. However, due to the distribution and number of gravity data, the poor resolution of the digital terrain model and the systematic error of levelling data, there exist unavoidably local biases between the national geoid models and the local geoid (Marc Véronneau, 1997, 2001; Derek Loo, 2002). The conclusion is also proved by comparing the ellipsoid/geoid separations calculated by CGG2000 and GPS/levelling data along the river. 13 centimetres maximal bias and 5 centimetres minimal bias are found in the comparison.

GPS/levelling method (geometric method) is appropriate for local precise geoid determination in small area (B.Erol, 2003). GPS/levelling points distributed ideally along the Saint John River at each tide gauge (Figure 1) provide a possibility to simulate accurately the local geoid undulation by a geometric method. Considering the orientation of Long Reach, north-south river segment is chosen as study area (Figure 1). The local geometric geoid model is designed as the following.

$$N = f(B,L) = a_0 + a_1\Delta B + a_2\Delta L + a_3\Delta B\Delta L + a_4\Delta B^2 + a_5\Delta L^2$$
$$\Delta B = B - B0 \qquad \Delta L = L - L0 \qquad (4)$$

Where, ($B0$, $L0$) is the centre position of the study area; (B, L) is the position of any point within the study area. The coefficient of the polynomial is a_i $_{(i=0,1...5)}$.

In the study area, 11 GPS/levelling points and 3 A-level GPS control points are used for the construction and test of the model. 10 of all known points are chosen for constructing model and testing the model interiorly; 4 other independent points are used for testing the model exteriorly. The statistical test result of the model is shown in Table 1 and verifies the credibility of the geometric model.

Model Test	Minimal Model Bias (cm)	Maximal Model Bias (cm)	Standard Bias(cm)
Interior Test	-0.1	1.67	±1.18
Exterior Test	0.06	1.89	±1.15

Table 1: The statistic test parameters of the geometric model.

For navigational safety, the surface of lower low water has been adopted as chart datum at each of river segment along the Saint John River (Fisheries and Oceans Canada website, Canada). The expression of the chart datum relative to the local geoid is also provided in the Table 2 (Saint John River chart description, 1996).
According to Table 2, it is not difficult to find variable chart datum and a stepped character. From Fredericton to Indian Town, the change of chart datum relative to the local geoid is less than 1 metre. However, at the river segment from Indian Town to Saint John, the change reaches more than 4 metres. The above character reflects the outstanding effect of the Bay of Fundy and the Reversing Falls for the tidal level of Saint John River, and shows the discontinuous chart datum in the entire river.

Station name	Chart datum (m)*	Station name	Chart datum (m)*
Saint John	4.19	Evandale	-0.70
Indiantown	-0.21	Belle Isle Bay	-0.71
Kennebecasis Bay	-0.34	Hampstead	-0.71
Ketepec	-0.34	Gagetown	-0.70
Westfield Beach	-0.50	Upper Gagetown	-0.73
Public Landing	-0.60	Maugerville	-0.80
Grand View	-0.68	Oromocto	-0.79
Oak Point	-0.70	Lower St Marys	-0.85
Hatfield Point	-0.70	Fredericton	-0.92
*: relative to the local geoid.			

Table 2: The relationship between the chart datum and the local geoid at each tide gauge along the Saint John River.

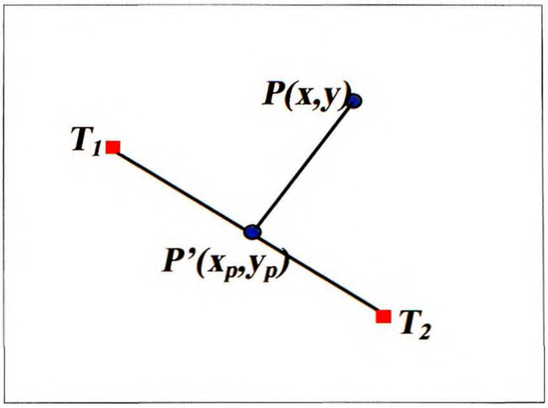

Figure 6: Cross-section linear interpolation.

This stepped profile does not affect GPS measurement since GPS does not refer to the vertical datum. However, if the relationship in Table 2 is adopted directly in GPS height transformation, a ladder-shape change will appear in the GPS tide solution. Thus, it is necessary to eliminate the stepped character and ensure the continuous variations of chart datums for the transformation from the orthometric height to chart height at RP. A cross-section linear interpolation method is adopted for fulfilling the precise transformation.
Connecting two adjacent tidal gauges $T_1(x_{T\text{-}1}, y_{T\text{-}1})$ and $T_2(x_{T\text{-}2}, y_{T\text{-}2})$, the equation of line T_1T_2 can be determined with the coordinates of the two tide gauges. For any point $P(x, y)$ between T_1 and T_2, the corresponding projecting point $P'(x_p, y_p)$ on the line can be determined by the following model (Figure 6).

$$x_p = \frac{x + k_0 y - k_0 b_0}{k_o^2 + 1} \qquad y_p = k_0 x_p + b_0 \qquad (5)$$
$$k_0 = \frac{y_{T-2} - y_{T-1}}{x_{T-2} - x_{T-1}} \qquad b_0 = y_{T-1} - k_0 x_{T-1}$$

The vertical separation $\Delta h_{p\text{-}cg}$ between chart datum and the local geoid at point P can be calculated by the following linear interpolation.

$$\Delta h_{p-cg} = \Delta h_{T-1} + S_{T1-p} \frac{(\Delta h_{T-2} - \Delta h_{T-1})}{S_{T1T2}} \quad (6)$$

Where, Δh_{T-1} (Δh_{T-2}) is the vertical separation between chart datum and the local geoid at tide gauge T_1 (T_2). S_{T1T2} is the distance between T_1 and T_2. S_{T1-p} is the distance between T_1 and the projecting point P'.

After acquiring the relationship between the chart datum and the local geoid at any position, the orthometric height H^o_{rp} at RP can be transformed to the chart height H^c_{rp}.

$$H^c_{rp} = H^o_{rp} + \Delta h_{cg} \quad (7)$$

The instantaneous water surface H^c_{ws} in chart height can be calculated by draft correction.

$$H^c_{ws} = H^c_{rp} + \Delta h_{draft} \quad (8)$$

Where, Δh_{draft} is the draft parameter.

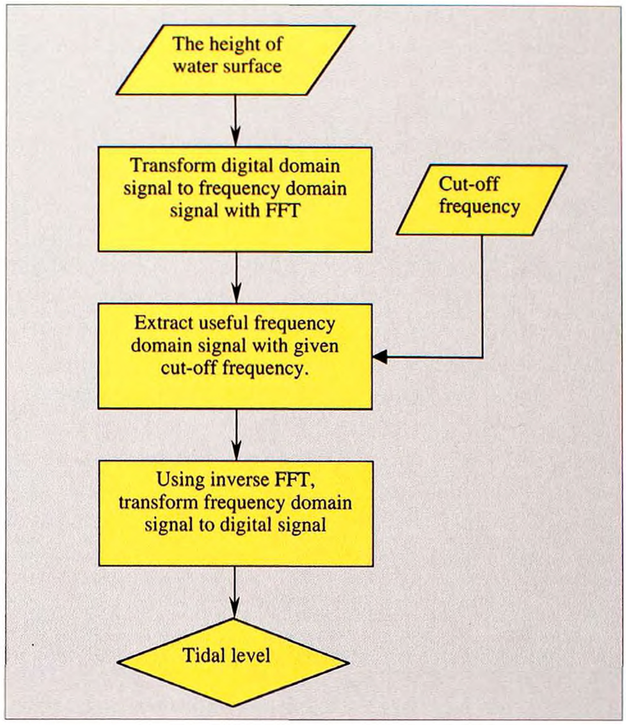

Figure 7: Flowchart showing tidal level extraction using FFT.

GPS Tide Data Filter

The water surface height H^c_{ws} is instantaneous and changes with the water state. However, tidal level reflects a more stable surface. In order to get the actual tidal level, we need filter the time series of instantaneous water surface and extract valid tidal signals.

The height of the water surface presents a complex blend signal which includes a lot of long-period and short-period signals. In the blend signal, as a main component, the tidal level is different from other signals in wave period/frequency. Generally, the period of tidal level is greater than 10 ~ 60 minutes. The period is obviously longer than the periods of instantaneous water surface noise.

In order to get the actual tidal level, a FFT (Fast Fourier Transformation) low-pass filter is designed and applied in this processing stream. The filtering procedure is shown in Figure 7. In the procedure, a cut-off period for distinguishing tidal level from the mixed signal should be set. Considering the actual tide behaviour of the Saint John River and the influence of the Bay of Fundy, a 15-minute cut-off period is used in the filter.

The Interpolation of Tidal Levels Derived from Tide Gauges

In order to prove the credibility of the GPS tide measurement result, the tidal levels derived from three tide gauges (Oak Point, Beulah Camp, and Days Landing) are introduced into the data analysis. The three tide gauges lie on a fairly straight line, thus a linear interpolation is used for calculating the tidal level TL_p at any point P between adjacent tide gauges.

$$TL_p = TL_1 \times w1 + TL_2 \times w2 \quad (9)$$

$$w_1 = \frac{1/d_{1-p}}{1/d_{1-p} + 1/d_{2-p}} \qquad w_2 = \frac{1/d_{2-p}}{1/d_{1-p} + 1/d_{2-p}}$$

Where, TL_1, TL_2 are respectively the tidal levels of adjacent two tidal gauges T_1 and T_2 at time t. $w1$ and $w2$ are the weight values given to the two tide gauges for determining the tidal level of any point P that lies between tide gauges T_1 and T_2. $w1$ and $w2$ are inversely proportional to distance d_{1-p} and d_{2-p}. d_{1-p} and d_{2-p} are the distances between tide gauge T_1 and point P, and the distance between tide gauge T_2 and point P respectively.

Experiments and Analysis of GPS Tidal Level Data Processing

In 17 May and 18 May, on-the-fly GPS tide measurement was implemented at Long Reach. The two

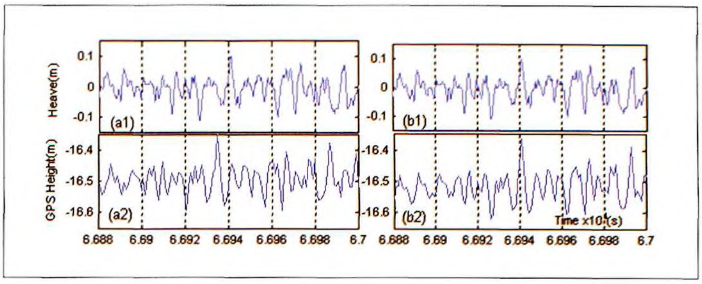

Figure 8: the existence and the elimination of the time offset between GPS clock and Simrad clock. 8a proves the existence of the offset between heave (a1) and GPS height (a2), which is eliminated well in 8b.

days' data were used for GPS tide data processing and analysis.

Figure 8 shows the successful implementation of time delay correction in the different height telegrams. Figure 8a shows the existence of substantial time delay between the two height sensors; Figure 8b shows the elimination of this time delay.

Comparing the raw height time series of PPK and RTK at corresponding GPS antenna phase centres, it is not difficult to find that the two time series are very similar in shape. However, in magnitude, there is about 40 centimetres separation between them, which results from attitude effect and the vertical distance between GPS antennae (Figure 9a, 10a). This is also shown clearly in Figure 10c. In order to remove the separation and acquire consistent PPK and RTK tide solutions, Attitude correction should be implemented to the raw PPK and RTK height time series.

Before attitude correction, the transformation from ellipsoidal height to chart height needs to be done. The transformed PPK and RTK height time series are shown in Figure 9b and 10b, which obviously differ from those in Figure 9a, 10a in magnitude and shape. The difference shows that it is only when the height transformation is applied in the data processing that the final GPS tidal level is practically valuable.

In order to further analyse attitude effect, an experimental processing procedure is used to deal with the raw PPK and RTK height series in Figure 9a. Two approximate instantaneous water surface

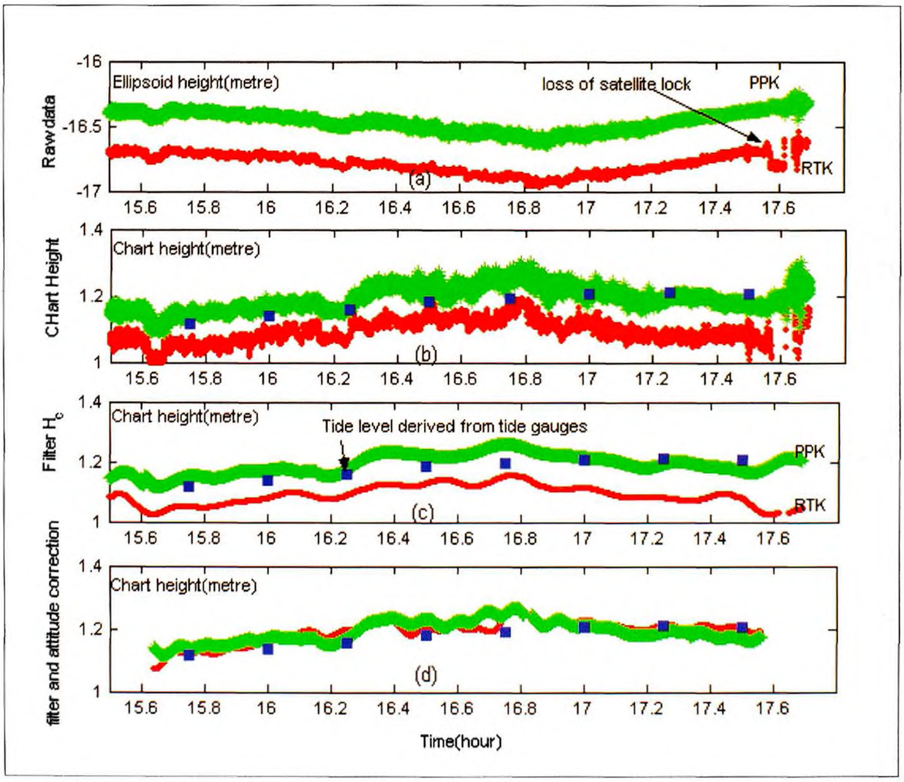

Figure 9: GPS tidal levels determined by PPK and RTK on 17 May 2004. (a): the raw PPK and RTK ellipsoidal height series at GPS antennae; (b): two approximate instantaneous water surface height series acquired by an experimental data processing (c): the results of filtered approximate instantaneous water surface height series; (d) the final PPK and RTK tide solutions achieved by a complete GPS tide data processing.

height series $H'^{c}_{PPK\text{-}ws}$ and $H'^{c}_{RTK\text{-}ws}$ are acquired and shown in Figure 9b, which are filtered and shown in Figure 9c. About 10 centimetres separation still exists between them (Figure 9b, 9c).

(10)

$$H'^{c}_{PPK-ws} = H_{PPK-GPS} + (\Delta h_{cg} - N) + Z_{PPK} + \Delta h_{drift}$$

$$H'^{c}_{RTK-ws} = H_{RTK-GPS} + (\Delta h_{cg} - N) + Z_{RTK} + \Delta h_{drift}$$

$$\Delta H'_{PPK-RTK} = (H_{PPK-GPS} - H_{RTK-GPS}) + (Z_{PPK} - Z_{RTK})$$

Where, $H_{PPK\text{-}GPS}$ and $H_{RTK\text{-}GPS}$ are PPK and RTK ellipsoidal height at corresponding antenna phase centres; Z_{ppk} (Z_{RTK}) is Z vector of PPK (RTK) antenna lever arm. ($\Delta h_{cg\text{-}N}$) is height transformation item; Δh_{drift} is draft correction;

The separation in Figure 9b/9c is explained by formula 10(c). Although the constant height difference (Z_{ppk} - Z_{RTK}) is eliminated in the entire separation between raw PPK and RTK height series, about 10 centimetres separation still exists between them due to attitude effect. Thus, attitude correction must be considered in GPS tide data processing.

In order to achieve final GPS tidal levels, a complete and strict data processing procedure, which involves time delay correction, height transformation, attitude correction, draft correction and data filter, is used to deal with the raw PPK and RTK height series. The final tide solutions are shown and compared with tide readings in figure 9d and 10d. The comparing results and statistic parameters are shown in figure 11 and table 3, which prove that GPS tide measurement and data processing methods are credible.

In GPS tide observation, the quality of GPS positioning solution may become lower even invalid due to some factors. For example, GPS satellite or radio signals are blocked by bridges or trees, or acute vessel attitude change leads to loss of satellite lock (Paul Denys, 2004). These problems are also presented in Figure 9a and 10a. Separate low-quality or invalid data can be repaired by the GPS tide data filter. However, continuous low-quality or invalid data may result in abnormal filtering result.

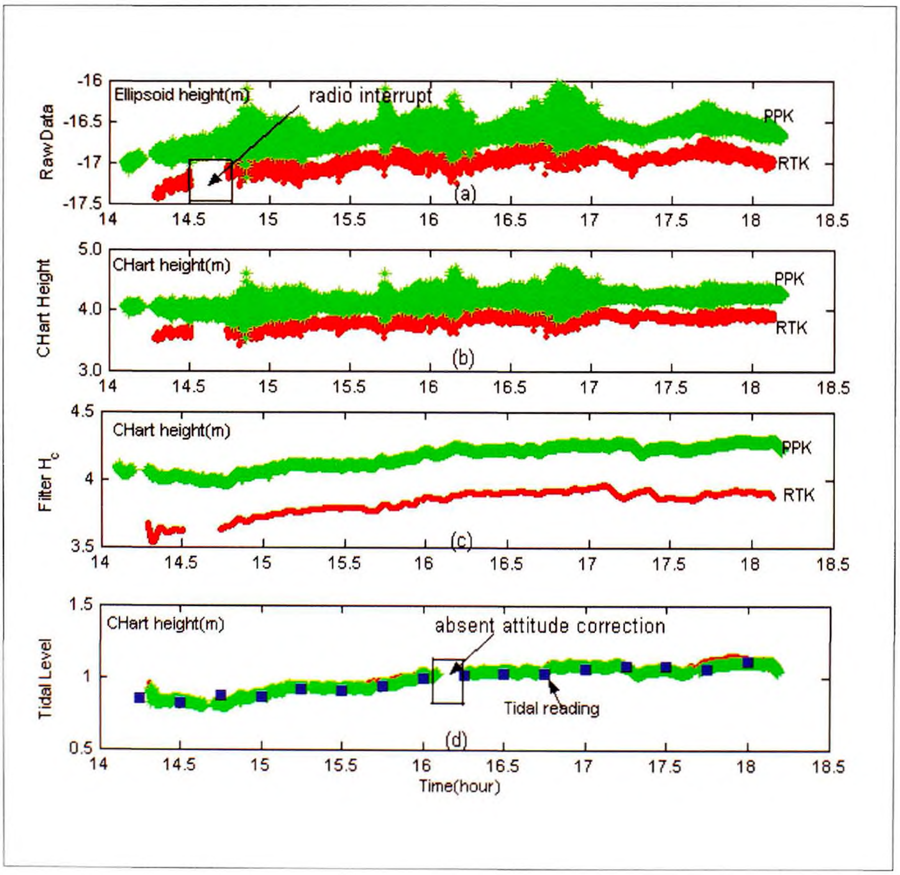

Figure 10: the GPS tidal levels determined by PPK and RTK on 18 May 2004. (a): The raw PPK and RTK ellipsoidal height series at GPS antennae; (b): the chart height series at PPK and RTK antennae; (c): the results of the filtered time series in (b). (d): the final PPK and RTK tide solutions achieved by a complete GPS tide data processing procedure.

Date	GPS tide solution	Minimal Bias (cm)	Maximal Bias (cm)	Standard Bias (cm)
May 17	PPK	0.9	4.2	±2.6
	RTK	0.2	3.8	±2.0
May 18	PPK	-0.1	5.0	±1.9
	RTK	-0.3	5.1	±2.9

Table 3: The statistic parameters determined by comparing GPS tide solutions and tide readings.

Similar interrupt problem is also found in attitude time series. Because of the switch of survey lines, attitude sample is stopped temporarily and leads to the interrupt at the same time segment in the final tidal solution (Figure 10d). The short-time break can also be recovered by the GPS tide data filter.

In PPK tide observation and data processing, the problem of radio interrupt can be ignored. Precise ephemeris and improved parameters can be adopted. Thus, generally, the accuracy and continuality of PPK tide solution are better than RTK's in theory (Paul Denys, 2004). The conclusion is also proved by the two days' observation data of PPK and RTK (Figure 9a 10a).

Conclusion and Advice

On-the-fly GPS tidal level measurement and data processing provide an alternative way of tidal level acquirement for precise hydrographic survey. The method ensures that tidal level can be accurately observed and determined within the scope of differential GPS valid work distance. Thus, the method has important applications for practicing hydrographers and the manufacturers of hydrographic survey hardware and software.

In order to achieve continuous and accurate GPS tide solution, it is recommended that both PPK and RTK techniques are adopted in GPS tide measurement so that the two GPS tide solutions can supply each other. For special river environment with widespread radio obstructions, PPK tide measurement is advised.

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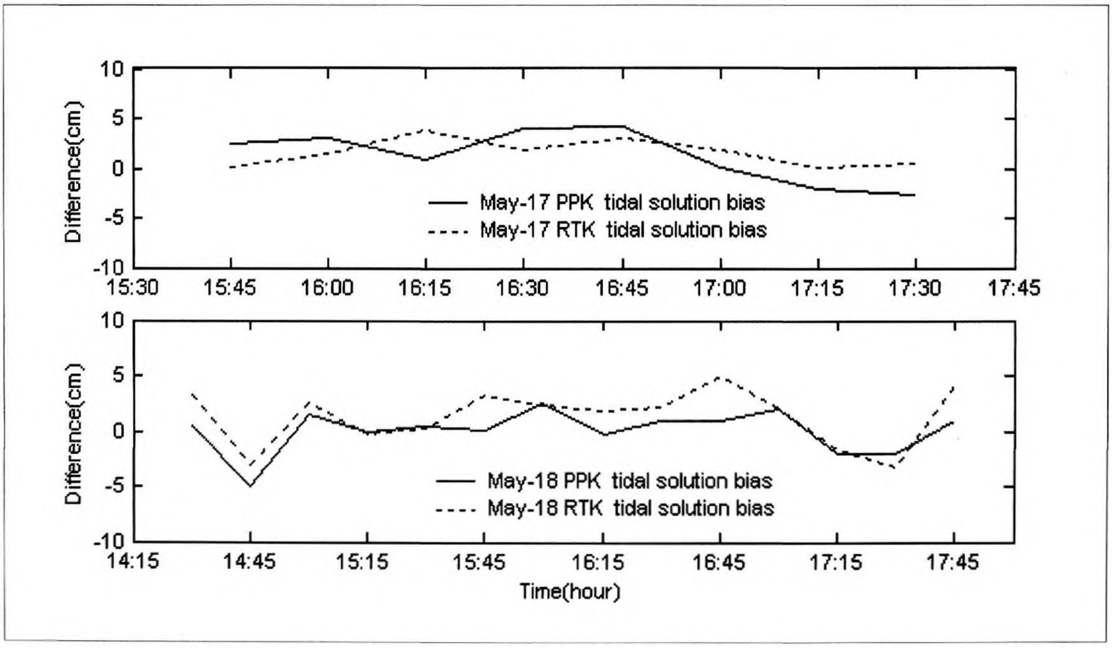

Figure 11: The biases between GPS tidal solutions and tidal readings.

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Biographies

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