Developing a Real Time Algorithm for Heave Determination Based on Single Frequency GPS Data

By

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Abstract

The advent of GPS Real-Time kinematic (RTK) in recent years has realized a significant advancement of GPS to provide three dimensional navigation at the centimeter level of accuracy. One of the fastest emerging trends in hydrographic surveying is the use of the vertical component of RTK GPS to determine real-time water level corrections. Accurate heave measurements are a critical component of the measurement of a hydrographic survey vessel's vertical motion. In the current research we submitted a new algorithm for computing the heave component in real time based on utilizing the ellipsoidal height produced by used single frequency GPS receiver positioning system in the bathymetry process. An evaluation process of the Heave-GPS based on a comparative study with the classical TSS-DMS05 heave compensator is discussed.

مستخلص

يتناول البحث شرح طريقة مطورة لأستخدام أجهزة النظام العالمي لتحديد الموقع في قياس الحركة الرأسية للمركبات المستخدمة في أعمال المساحة البحرية ، وذلك باستخدام أجهزة النظام العالمي اللحظية لتحديد الموقع احادية التردد . وقد تمت مقارنة النتائج المحسوبة من الطريقة الجديدة التي تم سردها في هذا البحث مع القيم المقاسة التي تم قياسها بواسطة أجهزة قياس الحركة الرأسية غالية الثمن بالمقارنة بأجهزة النظام العالمي لتحديد الموقع احادية التردد ، وأثبتت التجارب الحقلية الحصول على الدقة المطلوبة في أعمال المساحة البحرية وحسب مواصفات المنظمة الدولية للمساحة البحرية

Introduction

The term "differential GPS" (DGPS) encompasses a family of GPS relative positioning techniques. DGPS uses two or more GPS receiver-antenna units to position an unknown point or set of points relative to a known point or set of points. DGPS improves upon the positioning accuracy otherwise attainable in absolute point positioning methods, which use a single GPS receiver-antenna unit. However, DGPS can be divided into two primary surveying categories, namely meter level and centimeter level. Meter-level DGPS surveys utilize GPS code phase measurements. Normally, "DGPS" refers to meter level differential positioning based primarily on code phase measurements. Keep in mind that Meter-level DGPS has been used as the primary source of horizontal control for most of hydrographic surveying works. On the other hand, centimeter-level DGPS surveys utilize mainly GPS carrier phase measurements of the GPS carrier phase signal. There are several forms of centimeter-level DGPS surveying have been adopted by the GPS communities:

- *Post-Processed Kinematic GPS*
- *Real-Time Kinematic GPS*

The term “kinematic GPS” refers to the form of centimeter-level differential positioning which (primarily) uses carrier phase observables. Intuitively, “kinematic” GPS refers to use a rover receiver in conjunction with at least one static base station. All post-processing techniques require the kinematic GPS carrier phase “observables” to be continuously recorded. Use of the GPS carrier phase permits resolution at the millimeter level, provided the ambiguity of the integer-ambiguities of carrier phase wavelengths can be correctly fixed (Hofmann & Wellenhof 2001). Carrier phase ambiguity could be resolved in the presence of relative motion between two GPS receiver-antenna units “on-the-fly” (OTF). OTF refers to the mathematical technique that resolves GPS carrier phase integer ambiguities without requiring a GPS receiver to be stationary at any time.

Operationally, the kinematic GPS solution can be determined either in real-time or in post-processing. “Real time” in the term “real-time kinematic GPS” (RTK GPS) simply refers to the fact that the carrier phase corrections are transmitted in real time via some (wireless) data link; e.g., via very-high frequency (VHF), HF, or ultra-HF (UHF) radio transmission and applying the OTF algorithm to fix the related phase ambiguities in small parts of a second.

RTK is currently provided in various levels of configuration including single frequency GPS (L1), dual frequency GPS (L1/L2) and dual system (GPS+GLONASS). While most RTK systems are limited to baselines of 20-30 kilometers, the development of dual frequency RTK to minimize the effects of ionospheric errors and the use of multi-reference stations is now increasing the effective operational range (Mowlam et al (2003)).

The recent developments of the GPS real time kinematic (RTK) mode, using single or dual frequency receivers, have increased the precision of the height component. The precision is now to a point at which the RTK mode can be used to determine the height of the boat from which soundings are taken and the required order of survey precision can be met. Use of the water surface as the reference for reduction of soundings is no longer necessary. Real time measurement of the height of the boat also removes the need to:

- measure tidal height, including making any allowance for the time and range difference between the tide at the recording station and at the survey site (De Loach, S. R., 1995).
- measure heave (vertical rise and fall of the vessel due to swell and wave action)
- squat (vertical rise or fall of the vessel due to changing hydrostatic pressure around the hull as the boat moves through the water)
- measure vessel motion along multiple axes, RTK GPS receivers with a minimum of three antennae are needed. Various authors have discussed the measurement of vessel motion using GPS; they are referenced in Hughes Clack et al (1996). For a more complete discussion of measurement of multidirectional vessel motion (Cooper (1993)).

Heave is the vertical translation of the vessel relative to the average water level. Heave sensors typically utilize double integration of vertical acceleration, followed up with a high-pass filtering operation. Several approaches have been considered for measuring heave-induced errors in hydrographic survey, depth measurements. Heave motion of a survey vessel has traditionally been measured using inertial technologies, which can be expensive and have problems with usability and instability, resulting in higher survey costs and a significant hydrographer input burden. The most widely used approach has been to measure the survey boat attitude motions, along with depth and position, and correct the motion-induced errors during post survey processing. The survey boat attitude can be measured using several types of instruments. These instruments measurement systems can be grouped into the following general categories (David S. M. and M.N. Landers (1999)): (1) pendulum systems, (2) gyroscope systems, (3) accelerometer systems and (4) combination systems.

Pendulum Systems

Pendulum-based systems utilize gravity to maintain a pendulum in a vertical orientation so that as the instrument is tilted, the tilt is referenced to the vertical pendulum. The pendulum motion is often dampened by placing the pendulum in a fluid. Like the fluid-based system, the pendulum based system is subject to errors associated with horizontal accelerations. Again, there is a tradeoff between stability and response time based on the viscosity of the fluid used to dampen the pendulum motion. Accuracy of these instruments is about +/- 1E with a response time of about
20 Hz.

Gyroscope Systems

Vertical gyroscopes were developed to overcome the shortcomings of static inclinometer systems. Vertical gyroscopes employ a disc revolving on an axis. When the instrument is at rest there are no lateral forces, but as the instrument is rotated gyroscopic forces change and the angular rate can be determined. Gyroscopes can be expensive and often require an alternating-current power source. The power requirements, while readily available on a large manned vessel, are significant for a small manned or unmanned vessel. The time for gyroscopes to spin until they reach operational speed, drift over time, and sensitivity to shock is further disadvantages of gyroscopes for this application. Typical accuracy of these instruments is in the range of +/- 1E to +/- 3E.

Accelerometer Systems

Marine- and hydrographic-survey operations requiring compensation for vessel attitude commonly use accelerometer-based systems. Accelerometer-based systems have no moving parts and can measure heave, pitch, and roll. These systems typically employ three high-grade linear accelerometers. In addition to the triax of linear accelerometers, two angular accelerometers are often used to compensate for the horizontal accelerations. These instruments can achieve an accuracy of +/- 5 cm for heave and +/- 0.15E for pitch and roll and provide data rates of about 20 Hz.

Combination Systems

There are several systems available that combine one or more of the technologies already presented. Fluid-based systems have been combined with low-power gyroscopes to smooth the short-term inaccuracies of a fluid-based inclinometer caused by lateral accelerations. Some gyroscope systems use GPS to correct for drift or accelerometers to correct for lateral accelerations. These combination systems complement the strength and weaknesses of the various technologies and provide a system with better characteristics than is available with a single technology.

The Heave Algorithm

If the pseudorange and carrier phase, scaled as ranges, at a certain frequency *i* are denoted as $\rho_i(t)$ and $\lambda_i \varphi_i$, then the two equations, which relate these observations to the receiver-satellite geometric range and the biases contaminating these observations, can be formulated as:

$$\lambda_i \varphi_i(t) \quad = \quad R(t) + c(dt - dT) + \lambda_i N_i - I_i(t) + T + \varepsilon_\varphi \qquad (1)$$

$$\rho_i(t) \quad = \quad R(t) + c(dt - dT) + I_i(t) + T + \varepsilon_R \qquad (2)$$

Where:

φ_i = carrier phase of the current epoch, subscript i denotes to L1 or L2 (cycles)

λ_i = wavelength (m)

ρ = pseudorange (m)

R = geometric range between the station and the receiver (m)

c = speed of light (m/s)

I = ionospheric effect (m)

T = tropospheric effect (m)

ε_φ = carrier phase noise

ε_R = pseudorange noise

(t) = GPS-week time for the current epoch (s)

$dt - dT$ = Combined satellite and receiver clock offset (s).

By using the differencing techniques as described in (Hofmann W. et al., 2001)), all the correlated biases can be eliminated. Firstly the *single difference*, normally between two receivers, say *A* and *B* (subscripts), observing simultaneously the same satellite, say *j* (superscript) is formed in the following.

$$\begin{aligned} \lambda\varphi^j_A &= R^j_A(t) + c(dt - dT)^j_A + \lambda\ N^j_A - I^j_A(t) + T^j_A + b_A + \varepsilon^j_A \\ \lambda\varphi^j_B &= R^j_B(t) + c(dt - dT)^j_B + \lambda\ N^j_B - I^j_B(t) + T^j_B + b_B + \varepsilon^j_B \end{aligned} \qquad (3)$$

And by differencing equations (3), one obtains:

$$\lambda\ \Delta\varphi^j_{AB} = \Delta R^j_{AB}(t) + c(dt_B - dt_A) + \lambda\ \Delta N^j_{AB} - \Delta I^j_{AB}(t) + \Delta T^j_{AB} + \varepsilon^j_{\Delta\varphi_{AB}} \qquad (4)$$

The most important characteristics of the single difference observable is the removing of satellite clock biases. For another satellite k, the single difference equation between the two receivers A, B and the satellite k can also be written as:

$$\lambda\ \Delta\varphi^{k}_{AB} = \Delta R^{k}_{AB}(t) + c(dt_B - dt_A) + \lambda\ \Delta N^{k}_{AB} - \Delta I^{k}_{AB}(t) + \Delta T^{k}_{AB} + \varepsilon^{k}_{\Delta\varphi_{AB}} \qquad (5)$$

In order to remove the common errors in equation (2), namely, the receiver and satellite clock errors, the interchannel and the correlated part of the tropospheric and ionospheric refraction, double difference observables between two satellites *j, k* and two receivers *A, B* are built. Thus the double difference can be obtained by differencing equations (4) and (5) as:

$$\lambda\ \nabla\Delta\varphi^{jk}_{AB} = \nabla\Delta R^{jk}_{AB}(t) + \lambda\ \nabla\Delta N^{jk}_{AB} - \nabla\Delta I^{jk}_{AB}(t) + \nabla\Delta T^{jk}_{AB} + \varepsilon^{jk}_{\nabla\Delta\varphi_{AB}} \qquad (10)$$

It is worthwhile to mention that, although the double difference GPS measurements have eliminated the effect of some biases and reduced others, their drawback is that they are correlated. So, the mathematical correlation between observations must be determined, for more details about the mathematical correlation of the different types of differencing, one refers to (Hofmann-Wellenhof et al. 1994).

Additionally, to eliminate the time independent biases like the phase ambiguities, (Remondi, 1984) has suggested to difference *double differences* between two epochs t_1, t_2 which yields the trible difference as:

$$\lambda\nabla\Delta\varphi^{jk}_{AB}(t_1,t_2) = \nabla\Delta R^{jk}_{AB}(t_1,t_2) - \nabla\Delta I^{jk}_{AB}(t_1,t_2) + \nabla\Delta T^{jk}_{AB}(t_1,t_2) + \nabla\Delta\varepsilon^{jk}_{\delta\nabla\Delta\varphi_{AB}}(t_1,t_2) \qquad (11)$$

Where: $\nabla\Delta R^{jk}_{AB}(t_1,t_2) \equiv f(\Delta Latitude, \Delta Longitude, \Delta Ellip.Height)$

$\Delta Ellip.Height$: refers to *(h_2-h_1)* i.e. the computed heave

The last term of equation (11) combines the effect of the receiver multipath & noises. To see the effect of triple differences of Ionosphere, troposphere & noise on the triple phase observations, the triple phase observations were computed over a baseline Esmallia-10RM about of 40 km baseline conducted in Egypt at 17th May 2008 in static mode, where 1211000000 sec. was removed from the GPS time to make it writable. Hence, the reference-rover positions variation over time is zeros, in other words, the ranges triple differences are approaching zeros and the observed values expressing the rest terms of equation (11), namely the ionspheric, tropospheric noise triple differences residuals for the four satellites is outlined in figure (1). As it is shown in figure (1), the extreme values of the ionspheric, tropospheric and noise triple differences residuals are ranged between +0.3 & -0.3 L1 cycle.

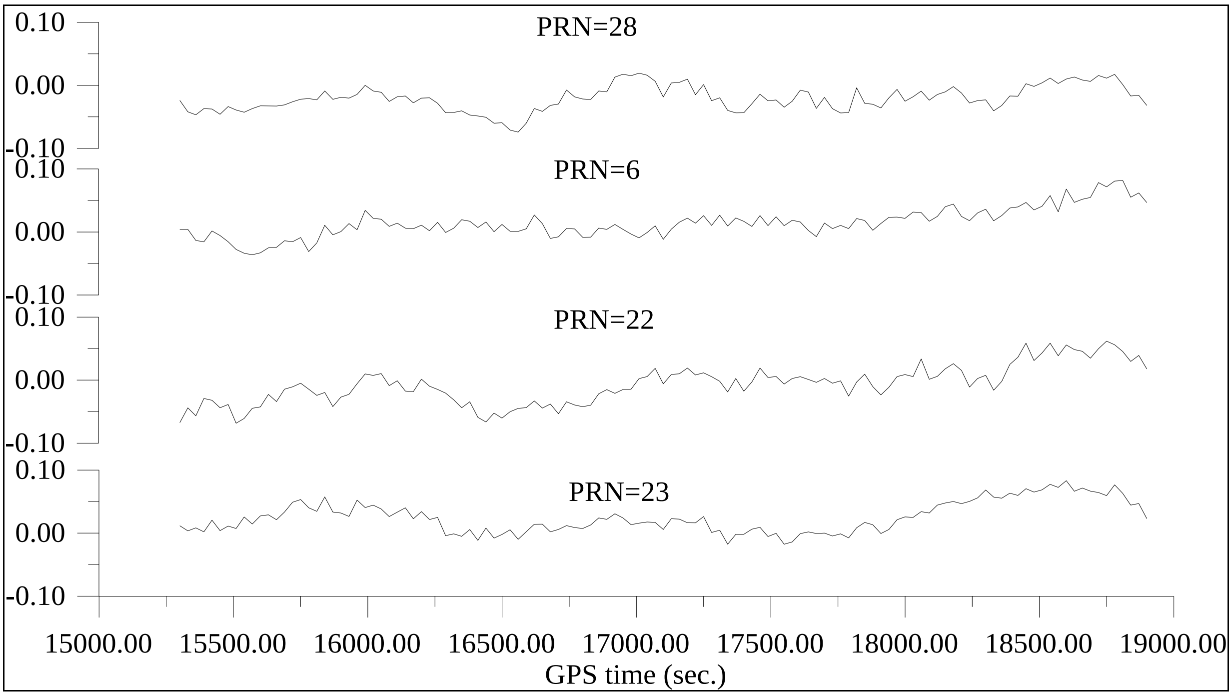

Figure (1)
The ionspheric, tropospheric trible and differences residuals (L1-cycle)

The above algorithm is characterized by it is free from the effect of the receiver clock drift; thus it does not need to apply any High Pass Filter. Additionally, the algorithm also does not need to apply any mathematical model for troposphere or ionosphere as well as the small size of noise compared with the algorithm described in (Blake S., C. Hill, and T. Moore (2008)).

Verification of the Developed Heave Algorithm in East Port-Said Port

To verify the aforementioned algorithm, a sea trial of the developed heave algorithm was conducted at 24 May 2008 in East Port Said Port with the help of Port Said Authority Surveying Staff, who made their survey launch is available. The trial was intended to test the performance of the developed heave algorithm as an alternative to the TSS-DMS05 Motion sensor based heave algorithms by collecting raw GPS data from three Trimble 4000 SSI receivers used in the trial, processing it through the developed heave algorithm and comparing the heave results to those obtained from TSS IMU based sensor. Keep in mind that two units of the three GPS were located as references for the trial, one base near to the tide gauge, and the second at the location of PS17, see figure (2). The last unit was installed on the survey Launch which was equipped with TSS-DMS05 Motion Sensor.

The first sea trial was made in the internal part of the navigational channel near to the Seaport. The results were depicted in figure (3). As it is shown in figure (3), the lower curve represents the induced heave as given by PDS2000 Software the product of Reson Co. (www.reson.com). The fluctuation or more accurately word the instability, of the heave produced by TSS at the beginning of the test is due to the maneuvering of the survey Launch. The resulted heave was ranged between -0.10 & 0.08 m. On the other side, the GPS heave computed by the developed algorithm was seemed to be more stable. Its values were ranged between -0.09 & 0.12 m.

The second trial was made in the external part of the navigational channel. The results were output in figure (4). As it is demonstrated in figure (4), the lower curve, the induced heave by TSS motion sensor is still suffering at the initial from the instability due to the launch maneuvering. Its values were ranged between -0.15 & +0.1m. On the other hand, in the upper curve, the GPS computed heave values were ranged between -0.10 & +0.08m.

The results of both tests confirm the needs to high update rate (20 Hz) GPS equipments such as S750 to be similar with the high rate of TSS motion Sensor. The RTK GPS high update date rate will show an increased level of performance over the heave solutions using 1 Hz data RTK and exhibited no adverse effects due to higher frequency heave motion (Scarfe, B. 2002).

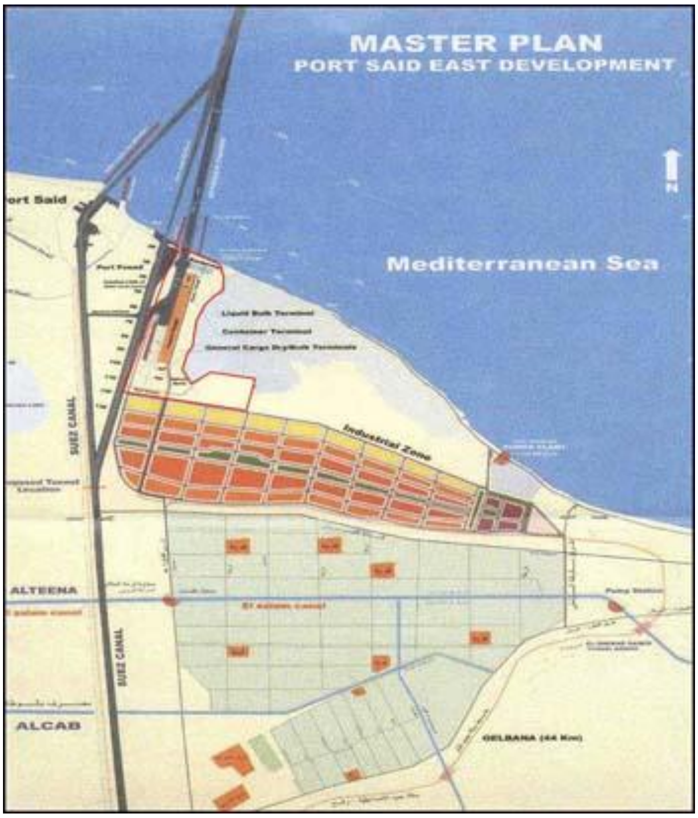

Figure (2)
The map location of East Port Said Port

Conclusion

The developed GPS heave algorithm can be used with all types of GPS receivers, single or dual receivers; processed in Post processing mode or in Real Time Kinematic mode. The GPS heave values computed from 1 Hz GPS recorded data was found to be inadequate for the measurement of the frequency of heave motion experienced by the vessel during the trial. The results of the sea trial show the ability of developed heave algorithm to measure heave to the accuracy required for at least IHO survey order. The RTK GPS high update date rate will show an increased level of performance over the heave solutions using 1 Hz data.

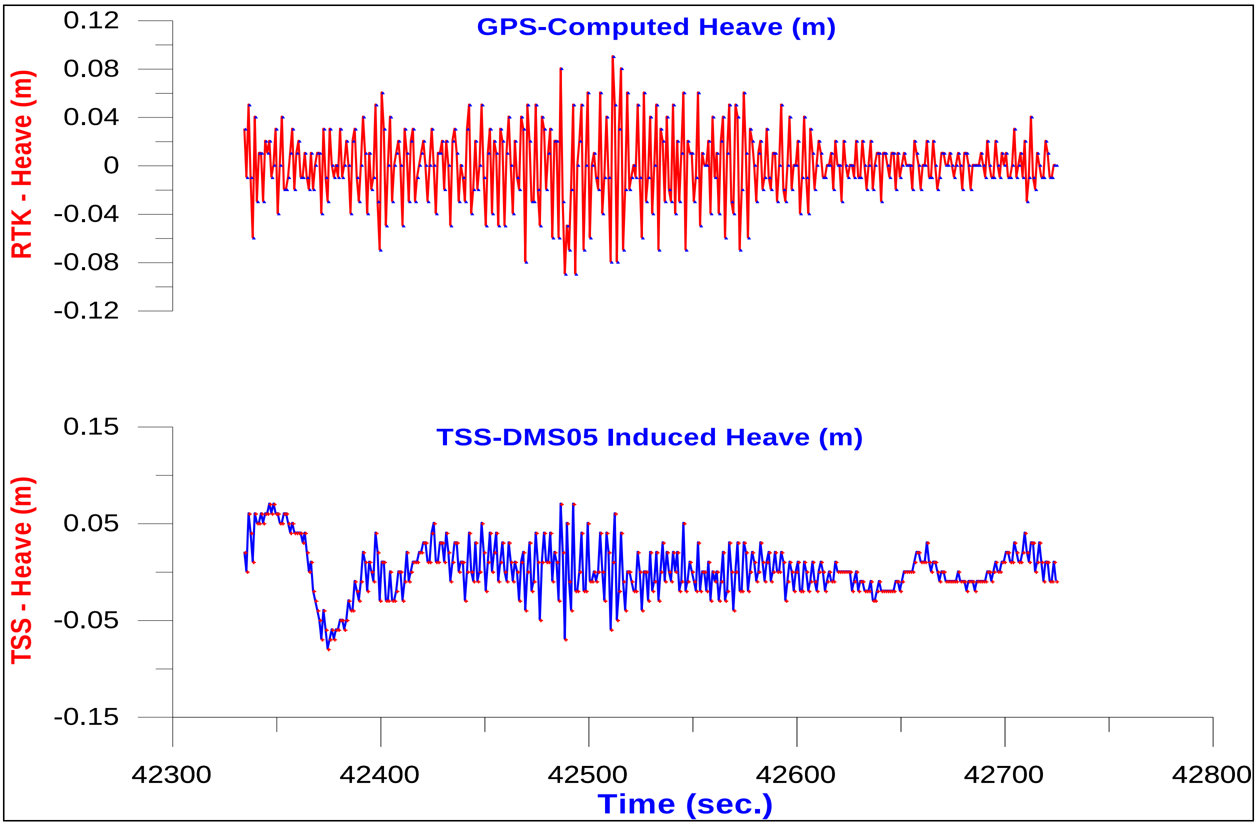

Figure (3)
The first sea trial GPS computed heave and TSS DMS05 induced heave

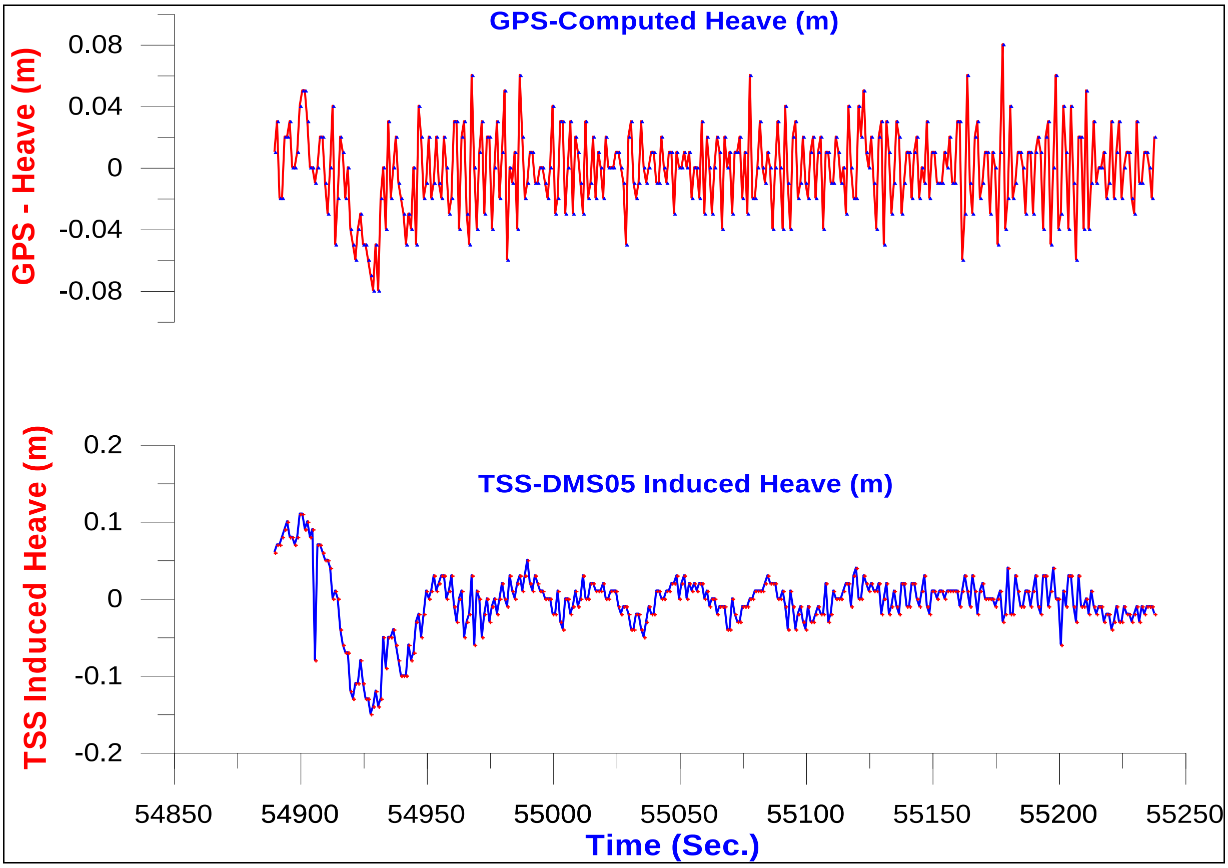

Figure (4)
The second sea trial GPS computed heave and TSS DMS05 induced heave

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