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Sub-Metre Accuracy for Stand Alone GPS Positioning in Hydrographic Surveying

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The accuracy that can be achieved by a single GPS receiver in stand-alone mode is around 10 metres with SA switched off; this is not adequate for most hydrographic studies. This study aims to improve this level of accuracy using a single geodetic receiver in stand-alone mode by applying a phase smoothing algorithm. The algorithm described in this study requires that the measurements be started from a known point for initialisation. The test site selected for the study is Halic bay, Istanbul. After GPS data were collected on a geodetic point for initialisation, the receiver was moved to a hydrographic vessel and trial measurements were performed along several survey profiles. The position of the vessel was calculated at every epoch using the carrier phase smoothing algorithm. In order to analyse the accuracy of the results, a second receiver collected data on another known point on the seashore during the whole session. The position of the vessel was accurately determined using a kinematic positioning method considering the data collected by both receivers. The results produced show that an accuracy of less than a metre can be achieved using the approach considered in this study.

KEY WORDS

1. GPS. 2. Phase Smoothing. 3. Hydrography.

1. INTRODUCTION. The positioning accuracy requirements in marine and hydrographic applications are varied. In marine applications, 50–100 metre accuracy might be sufficient for oceanographic and general navigation purposes whereas an accuracy of several metres is essential for ships approaching harbour. On the other hand, hydrographic applications are usually categorized with respect to the accuracy requirements as low, medium and high. Whilst the first one requires ± 100 m positional accuracy, the second requires ± 1 to 10 m positional accuracy. The highest accuracy required is $\pm 0{\cdot}1$ m in position and height (Seeber, 1993).

GPS techniques can be used in a wide range of marine survey applications for a variety of reasons, mainly due to being independent of weather conditions, having no requirement for the inter-visibility of survey points and being able to conduct surveying during night and day, and providing accurate and reliable results. Positioning

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with GPS in marine and hydrographic applications can be performed using two main approaches: single point positioning (stand-alone positioning) and differential positioning techniques. Since May 2000, when the US Government turned off SA, the stand-alone positioning can achieve accuracies of approximately 10 metres. For higher accuracy requirements differential techniques, such as differential GPS or real time kinematic methods, should be used.

The stand-alone approach can be easily applied to navigation and some hydrographic applications since there is no need for secondary data from other sources. To improve the accuracy of stand-alone positioning several methods have been introduced in the literature. A common way is to create a pseudo-range/carrier phase combination that smoothes the pseudo-range data. The basis of all data smoothing techniques is to derive the "rate of change of range from the carrier phase data and to combine this with the absolute measurement of range provided by the pseudo-range data" (Rizos, 1999). This technique was first investigated extensively in 1982 by Hatch using carrier phase measurements to filter the pseudoranges (Ashkenazi *et al.*, 1990). Slight variations of the technique were proposed by other investigators, including Lachapelle *et al.* (1987), Lachapelle *et al.* (1995), Cannon and Lachapelle (1992). Another initialisation approach for a phase smoothing algorithm is given by Westrop *et al.* (1989). The main idea of their algorithm is that the initial range can be computed precisely from the known coordinates of an initial point. It can also be computed by averaging a number of observed pseudoranges over a period of time. In this study, the algorithm is employed to compute the coordinates of the vessel locations. The results are then compared with the coordinates obtained from differential kinematic positioning.

2. PHASE SMOOTHING METHODS.

The pseudorange is a measure of distance between the GPS receiver and the GPS satellite, expressed by:

$$PR = R + c(dt_R - dt_S) + d_{ion} + d_{trop} \tag{1}$$

where, R is geometrical distance between satellite and receiver, dt_R and dt_S are the receiver and satellite clock offsets, d_{ion} and d_{trop} are the atmospheric effects on the observations, and c is the speed of light in vacuum.

The term 'code smoothing with carrier phase observation' refers to the method of combining code and carrier-phase measurements into a smoothed pseudorange. Phase-smoothed pseudoranges are observations that have been derived from both code and carrier measurements. For the single frequency case the phase smoothing algorithm is expressed by the following equation (Westrop *et al.*, 1989):

$$PR(t_i)_{sm} = PR(0) + \lambda[\Phi(i) - \Phi(0)] \tag{2}$$

where $PR(t_i)_{sm}$ is the phase smoothed pseudorange, $PR(0)$ is the initial pseudorange, Φ is the phase measurement and λ is the GPS signal wavelength. According to the method, the change in the range between initial and ith epochs measured by the carrier phase is added to the reference pseudorange to give phase-smoothed pseudoranges. The schematic representation of this algorithm is shown in Figure 1. The initial range, $PR(0)$ in Equation (2), is computed accurately from the known coordinates of an initial point. If a cycle slip has occurred and cannot be repaired,

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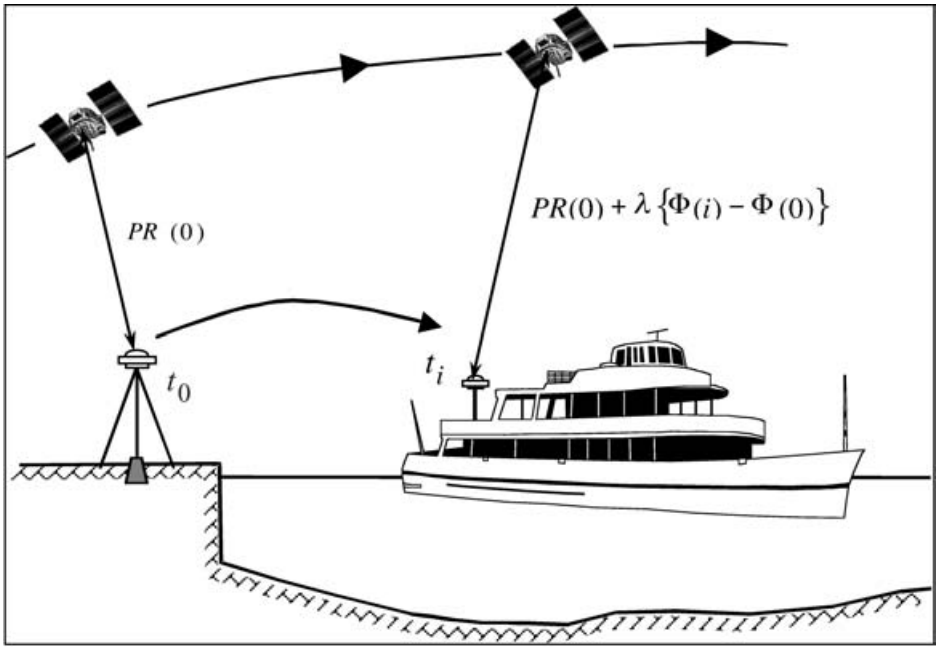


Figure 1. Schematic representation of the proposed phase smoothing algorithm.

then a new initial pseudorange is computed and the process is restarted at the current epoch (Westrop *et al.*, 1989; Hofmann-Wellenhof *et al.*, 1992; Lachapelle *et al.*, 1987);

$$PR(t_i)_{sm} = w \,.\, PR(t_i) + (1-w)[PR(t_{i-1})_{sm} + \Phi(t_i) - \Phi(t_{i-1})] \tag{3}$$

where w is a time dependant weight factor. For the first epoch w takes the value of 1. With the accumulation of further epochs the weight is continuously reduced and thus the influence of the carrier phase data is increased. A reduction rate of 0·01 in the weight from epoch to epoch has been recommended for 1 sec kinematic data. In such a case, after 100 epochs corresponding to 100 sec, only the smoothed value from the previous epoch (augmented by the carrier phase rate of change) is taken into account (Rizos, 1999). In the case that a cycle slip has occurred, the weight is reset to 1 and the smoothing process is restarted. It should be noted that cycle slips must be detected but do not have to be repaired in this approach (Hofmann-Wellenhof *et al.*, 1992).

3. FIELD STUDY AND DATA COLLECTION.

The test measurements were conducted at the Halic bay, Istanbul, in July 2002. The Halic, commonly known as the Golden Horn, is a natural water body approximately 8 km long and 200–700 m wide. Its depth extends to approximately 50 m (Figure 2).

Control points were established around the study area and coordinated by GPS. The locations of these points were determined on the shore such that they have clear visibility for all possible satellites. The GPS measurements were performed with dual frequency Leica System 300 GPS receivers in static mode (the accuracy is about

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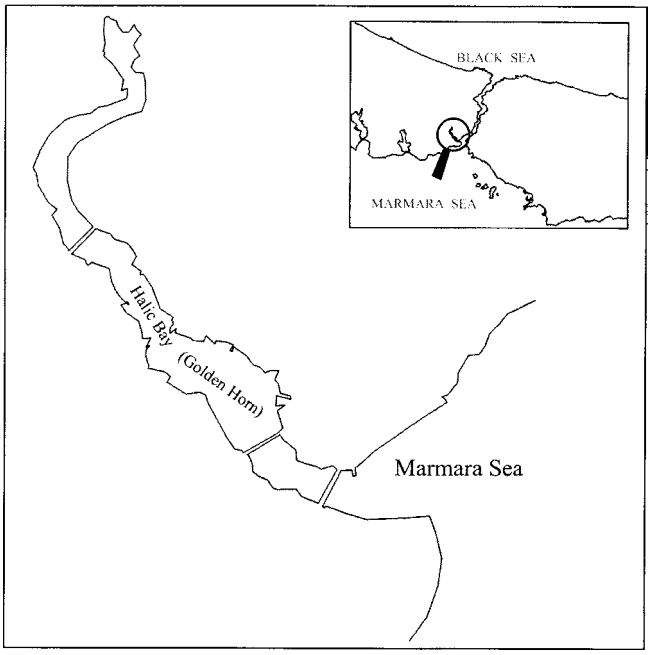


Figure 2. The study area, Halic Bay.

5 mm + 1 ppm). The data were collected every 10-seconds. The constituted GPS network was tied to one of the IGS stations, ISTA, located on Istanbul Technical University campus, hence the coordinates of these geodetic points were calculated in the latest ITRF reference frame. Post-processing of the raw data and adjustment were accomplished with Leica, SKI software. This resulted in ellipsoidal latitude, longitude and height values for each point.

After these pre-studies, the testing procedure was started. The data were collected with two geodetic GPS receivers, one of which was set up on the known point, which had been established and coordinated during the pre-study stage. This took only a few minutes for initialisation and the receiver was moved to the vessel. Trial measurements were performed along several survey profiles as depicted in Figure 3. During this same time period, the stationary receiver on the shore collected data to calculate precise positions of the vessel with common relative processing technique.

4. PROCESSING COLLECTED DATA. In this stage of the study, the positions of the vessel were calculated for every epoch using both phase-smoothed ranges computed from Equation (2) and raw pseudoranges using Equation (1). An in-house program, coded in Fortran-77, was employed. The program, developed by the first and third authors of this paper (Cenesiz *et al.*, 1999), was previously written to process GPS pseudorange data. The program was enhanced to perform the phase smoothing algorithm described in section 2.

4.1. *Calculation of atmospheric corrections.* The atmospheric corrections are carried out to eliminate the tropospheric and ionospheric effects. Tropospheric effect

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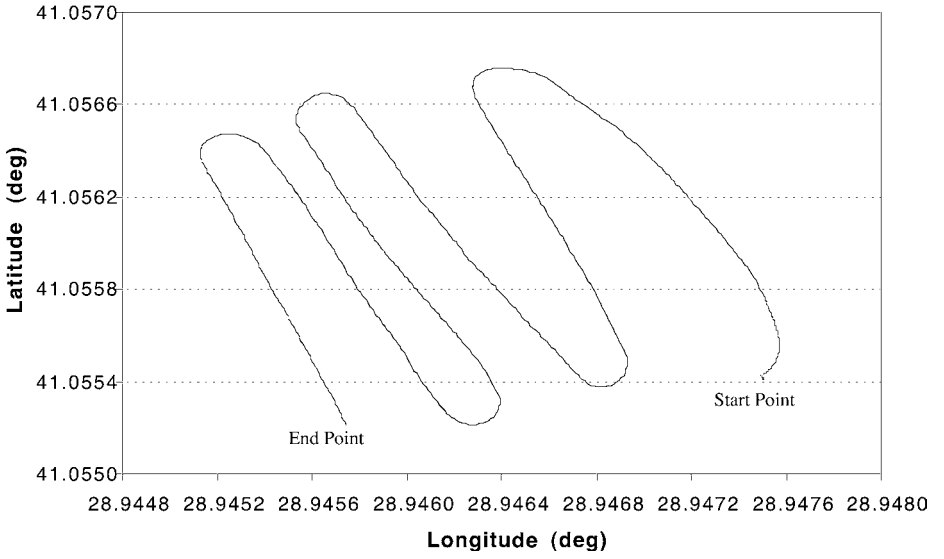


Figure 3. Trajectory of the vessel along the hydrographic survey.

is a function of the satellite elevation angle and the altitude of the receiver and is dependent on the atmospheric pressure, temperature and water vapour pressure. In the program this effect was calculated by a Saastamoinen Model with the following refined formula (Hofmann-Wellenhof *et al*., 1992):

$$d_{trop} = \frac{0{\cdot}002277}{CosZ}\left[p + \left(\frac{1255}{T} + 0{\cdot}05\right)e - BTan^2Z\right] + \delta R \tag{4}$$

where, Z denotes the zenith distance of the satellite, p is the atmospheric pressure in mbar, T is the temperature (Kelvin) and e shows the partial pressure of water vapour in mbar. B and δR are the correction terms estimated from the table values. While B is dependent upon the altitude of the station, δR is dependent upon both the altitude of the station and the elevation angle of the satellite (Hofmann-Wellenhof *et al*., 1992).

The ionosphere, extending in various layers from about 50 km to 1000 km above earth, is a dispersive medium with respect to the GPS radio signal. There are several models for reducing or removing the effect of the ionosphere. In this study the Klobuchar model, which is expressed in the following equations, is used to compute the time delay due to the ionosphere in the zenith direction (in seconds):

$$t_{Z_{ion}} = DC + A\,.\,Cos\left(\frac{2\pi(t - t_0)}{P}\right) \tag{5}$$

where, DC, A, t_0, t and P are the base ionospheric time delay, the amplitude of the ionospheric delay function, local time of maximum ionospheric correction, the local time at receiver and the period of the ionospheric delay function, respectively. The DC and t_0 terms are held constant at 5 nsec and 14 h (504,000 sec) local time,

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respectively. The quantities A and P are modelled as third-order polynomials:

$$A = \sum_{n=0}^{3} \alpha_n \varphi_m^n \text{ (seconds)} \tag{6}$$

$$P = \sum_{n=0}^{3} \beta_n \varphi_m^n \text{ (seconds)} \tag{7}$$

where, φ_m is the geomagnetic latitude of the ionospheric subpoint, and α_n and β_n coefficients are placed in the satellite navigation message (Feess and Stephens, 1987). The $t_{Z_{ion}}$ must be scaled by the mapping function to determine the time delay along the slant direction to the satellite by:

$$d_{ion} = t_{Z_{ion}} . SF \tag{8}$$

$$SF = Sec\left[Sin^{-1}\left(\frac{rCos(Elev)}{r+h}\right)\right] \tag{9}$$

where *Elev* is the elevation angle to the satellite, r is the mean Earth radius and h is the mean ionospheric height (Rizos, 1999). Further details of the derivation of these equations can be found in Klobuchar (1987). The estimated values of d_{ion}, which are in metric units, were added to the phase measurements and subtracted from pseudoranges.

4.2. *Cycle slip detection and repairing*. A cycle slip is defined as a discontinuity or a jump in the GPS carrier-phase measurements. It may occur briefly or may remain for several minutes or more. A cycle slip occurs when tracking of the incoming carrier signal is interrupted due to signal path obstruction (i.e. trees, buildings, bridges, mountains, etc.), low signal-to-noise ratio, multipath, high receiver dynamics, low satellite angle or failure in the software of the receiver. The cycle slip treatment procedure is made up of detection, determination of its size and repair. Detection and determination of cycle slip require the location of the jump and the determination of its size. Detection is realized by a testing quantity. Various methods are used in the literature to determine the testing quantity (Lichtenegger and Hofmann-Wellenhof, 1989). In this study, a special L_1 and L_2 combination known as ionospheric residuals was used (Goad, 1986).

$$\delta\phi(t) = \Phi_{L_1}(t) - \frac{f_{L_1}}{f_{L_2}} \Phi_{L_2}(t) \tag{10}$$

where, Φ_{L_1} and Φ_{L_2} are the phases of the two carrier waves L_1 and L_2, f_{L_1} and f_{L_2} are the frequencies of the satellite signals. If no loss of phase lock occurs, the value of $\delta\phi(t)$ varies slightly where epoch-to-epoch changes are due only to the ionospheric effects. The main advantage of the method is that it does not require any additional information such as satellite and station coordinates. When the variation in the test quantity (Equation 10) is greater or equal than 0·28 cycles (i.e. much larger than the noise level), a cycle slip occurs (Bastos and Landau, 1988).

Based on Equation (10), different detection and repairing techniques have been developed. In this study, a Kalman filter was applied to determine and recover cycle slips as it was found to be more suitable for kinematic measurements (Bastos and Landau, 1988). In this approach, Kalman filtering was used to predict subsequent

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observation values (Equation 13) that were then compared with the observed ones to detect cycle slips. In this study, the discrete Kalman filter with the following formulas was used (Goad, 1986; Bastos and Landau, 1988; Collin and Warnant, 1995);

System and measurement models;

$$X_k = \Phi_{k-1} X_{k-1} + W_{k-1}, \quad W_k \approx N(0, Q_k) \tag{11}$$

$$Z_k = H_k X_k + V_k, \quad V_k \approx N(0, R_k) \tag{12}$$

The state and covariance extrapolation equations;

$$\hat{X}_k(-) = \Phi_{k-1} \hat{X}_{k-1}(+) \tag{13}$$

$$P_k(-) = \Phi_{k-1} P_{k-1}(+) \Phi_{k-1}^T + Q_{k-1} \tag{14}$$

The measurement updating relations;

$$K_k = P_k(-) H_k^T [H_k P_k(-) H_k^T + R_k]^{-1} \tag{15}$$

$$\hat{X}_k(+) = \hat{X}_k(-) + K_k [Z_k - H_k \hat{X}_k(-)] \tag{16}$$

$$P_k(+) = (I - K_k H_k) P_k(-) \tag{17}$$

where, W is the random forcing function with a mean of zero, Q the system driven noise matrix, Z is the vector of measurements, V is the measurement noise with a mean of zero, R is the measurement noise matrix, P is the covariance matrix of the estimated vector and K is the gain matrix. The symbols (–) and (+) indicate extrapolated and updated quantities respectively. The state transition model (X) and state transition matrix (Φ) are:

$$X = \begin{bmatrix} y \\ \dot{y} \\ \ddot{y} \end{bmatrix} \quad \text{and} \quad \Phi = \begin{bmatrix} 1 & \Delta t & \frac{1}{2}\Delta t^2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix} \tag{18}$$

where Δt is the observation sampling rate. The measurement noise matrix R is taken as scalar, $2{\cdot}5 \times 10^{-3}$ (cycle^2). The system noise matrix Q is diagonal. For phase measurements (Equation 10) the diagonal elements of the matrix are (Bastos and Landau, 1988);

$$diag(Q) = [10^{-6} \quad 10^{-8} \quad 10^{-10}] \ (cycle^2 - cycle^{-2}) \tag{19}$$

These Kalman filtering procedures were applied to the data set considered in this research to detect possible cycle slips, but none was found.

4.3. *Determination of vessel coordinates using phase smoothing, single point positioning and differential GPS techniques.* In order to accomplish the main objective of this study the aforementioned phase smoothing method was applied to the test data. Survey vessel coordinates were calculated for every measurement epoch by raw pseudorange solution using Equation (1) and the phase smoothing using Equation (2). The vessel positions were also determined by Leica SKI software using, in addition, the stationary receiver's data so as to make a better comparison between the results. This method produced an estimated coordinate accuracy of a few centimetres. The results of both methods were compared and statistical results are presented in Table 1. It is clear from the table that the carrier phase smoothing can

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Table 1. Comparison of the results of SPP and phase smoothing.

Methods	Latitude (m)				Longitude (m)			
	max	min	mean	RMSE	max	min	mean	RMSE
Differential solution – SPP (Eq. 1)	−6·72	−4·35	−5·61	5·65	−4·76	−2·50	−3·61	3·66
Differential solution – Phase smoothing (Eq. 2)	−0·14	0·01	−0·08	0·09	0·25	−0·08	0·10	0·13

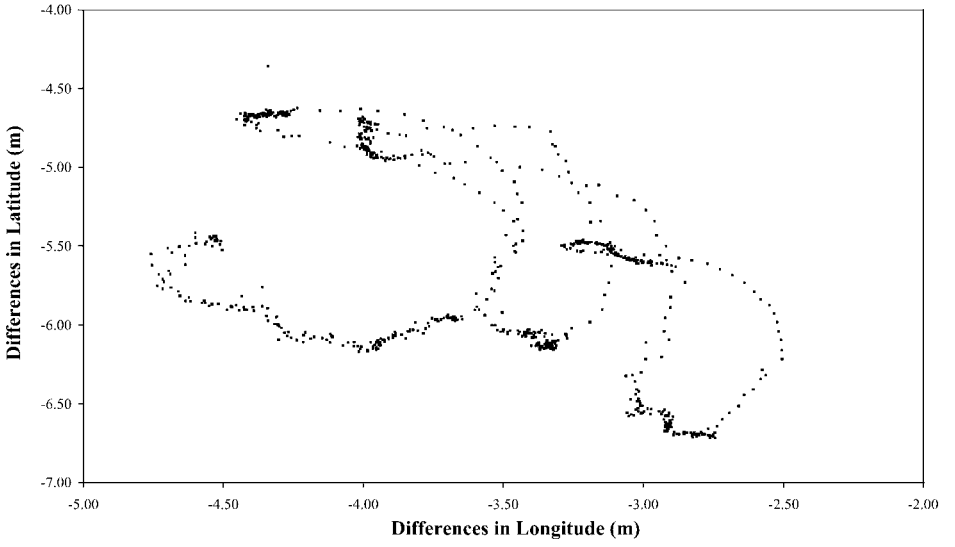


Figure 4. Coordinate differences between differential and single point positioning using pseudoranges (Equation 1).

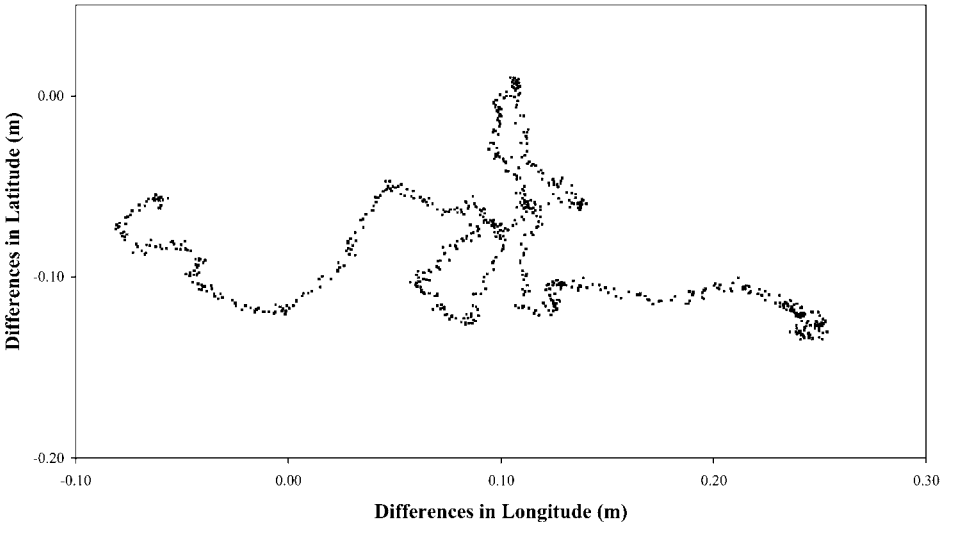


Figure 5. Coordinate differences between differential and phase-smoothing method using Equation (2).

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provide accuracies of better than a metre. Such levels of accuracy can certainly meet the requirements of most hydrographic applications. The differences between the differential and single point positioning methods are shown in Figure 4, whilst the differences between the differential and phase smoothing methods are depicted in Figure 5. It can be seen from Figure 4 that the average difference (i.e. error) is about 4 metres in longitude and about 6 metres in latitude. On the other hand, the differences in Figure 5 clearly show the superiority of the phase smoothing method over single point positioning technique as it produced results with a maximum error of 25 cm for the test data used in this research. This indicates considerable improvement in the estimation of positions.

5. CONCLUSIONS. This study introduces an approach to accurately estimate the coordinates of a near-shore vessel using a single GPS receiver by applying a phase smoothing algorithm. The main requirement of the proposed approach is to start the measurements from a known point solely for initialisation purpose. Therefore, the success of the approach is highly dependent on the accuracy of the computed initial ranges. Another factor that may affect the accuracy of the results is the occurrence of cycle slips during the measurements. In order to determine cycle slips in our dual frequency data, Kalman filtering was utilised. It should be pointed out that the technique requires dual frequency data. It can be noticed from the results that the positioning accuracy has considerably increased by using phase-smoothing technique although the measurements were collected using a single geodetic receiver. The level of accuracy achieved by the described approach could be ideal for many near-shore marine and hydrographic applications.

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REFERENCES

Ashkenazi, V., Moore, T. and Westrop, J. (1990). Combining pseudo-range and phase for dynamic GPS, *Proceedings of IAG Symposium on Kinematic Systems in Geodesy, Surveying and Remote Sensing*, Banff, Canada.

Bastos, L. and Landau, H. (1988). Fixing cycle slips in dual-frequency kinematic GPS-applications using Kalman filtering. *Manuscripta Geodaetica*, **13**, 249–256.

Cannon, M. E. and Lachapelle, G. (1992). Analysis of a high performance C/A code GPS receiver in kinematic mode. *Navigation*, **39**, 285–300.

Cenesiz, F., Saka, M. H., Nas, S. and Ozsamlı, C. (1999). A method to guarantee the continuity of GPS in urban environments, *Proceedings of the International Symposium on Remote Sensing & Integrated Technologies*, Istanbul, Turkey.

Collin, F. and Warnant, R. (1995). Application of the wavelet transform for GPS cycle slip correction and comparison with Kalman filter. *Manuscripta Geodaetica*, **20**, 161–172.

Feess, W. A. and Stephens, S. G. (1987). Evaluation of GPS ionospheric time-delay model, *IEEE Transactions on Aerospace and Electronic Systems*, **AES-23**, 332–338.

Goad, C. C. (1986). Precise positioning with the GPS, In *Lecture Notes in Earth Sciences: Applied Geodesy*, 17–30.

Hofmann-Wellenhof, B., Lichtenegger, H. and Collins, J. (1992). *Global Positioning System: Theory and Practice*, Springer-Verlag.

https://doi.org/10.1017/S0373463303002571 Published online by Cambridge University Press

Klobuchar, J. A. (1987). Ionospheric time-delay algorithm for single frequency GPS users, *IEEE Transactions on Aerospace and Electronic Systems*, **AES-23**, 325–331.

Lachapelle, G., Falkenberg, W. and Casey, M. (1987). Use of phase data for accurate GPS differential GPS kinematic positioning. *Bulletin Géodésique*, **61**, 367–377.

Lachapelle, G., W. Klukas, R., Roberts, D. and Qiu, W. (1995). One-metre level kinematic GPS point positioning using precise orbits and satellite clock corrections. *Geomatica*, **61**, 193–203.

Lichtenegger, H. and Hofmann-Wellenhof, B. (1989). GPS-data preprocessing for cycle-slip detection. *Proceedings of IAG Symposium on Global Positioning System: An Overview*, Springer-Verlag.

Rizos, C. (1999). *Principles and Practice of GPS Surveying*, See also http://www.gmat.unsw.edu.au/snap/snap.htm.

Seeber, G. (1993). *Satellite Geodesy, Foundations, Methods and Applications*. De Gruyter.

Westrop, J. M., Napier, M. E. and Ashkenazi, V. (1989). The use of phase for kinematic positioning by GPS. *Proceedings of IAG Symposium on Global Positioning System: An Overview*, Edinburgh, UK.

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