2019 IMEKO TC-19 International Workshop on
Metrology for the Sea
Genoa, Italy, October 3-5, 2019

GPS precise positioning techniques for remote marine applications

Anna Innac [1], Antonio Angrisano [2], Salvatore Gaglione [1] and Nicola Crocetto [3]
[1] *Parthenope University of Naples, Department of Science and Technologies, Naples, Italy;*
anna.innac@uniparthenope.it; salvatore.gaglione@uniparthenope.it
[2] *G. Fortunato University, Benevento, Italy; a.angrisano@unifortunato.eu*
[3] *Luigi Vanvitelli University of Campania, Department of Engineering, Naples, Italy; nicola.crocetto@unicampania.it*

Abstract **– Marine geodesy, offshore surveys and physical oceanography are usually related to the highly precise kinematic positioning of surveying platforms such as vessels, buoys and aircrafts. Currently, the Global Navigation Satellite Systems (GNSS) can provide a kinematic positioning accuracy of decimeter to centimeter level in relative mode, being potentially an appropriate choice for determining marine platform positions. However, these positioning techniques are related to the presence of reference stations and are not applicable in remote areas. In this work, two approaches are considered to determine the altitude variations of GPS antenna, which is an important parameter for the analysis of a ship motion. In detail, time-differencing of carrier phase measurements and precise point positioning approaches are applied on static data, collected by a single-frequency receiver, in order to assess the vertical variations performance.**

I. INTRODUCTION

Nowadays the vessel navigation is supported by a variety of independent sources of navigational information. The Global Navigation Satellite Systems (GNSS) is considered the key component in maritime navigation for provision of an absolute position, velocity and precise time (PVT) information.

Techniques of precise positioning have been developed and largely adopted for new maritime applications, related to accurate positioning requirements for anchoring or manoeuvring floating platforms, control of maritime works, sea level measurement and hydrographic surveying.

For example, buoys and ships, equipped with GNSS, are used to measure sea level for validation/calibration of satellite radar altimetry [1]. Using kinematic GNSS precise relative positioning for vertical control in hydrographic surveys is now a commonplace after being in a research-to-operations mode for several years [2]. Accurate positioning of ships and buoys will provide valuable information of the Sea Surface Height (SSH) to complement satellite altimetry data or as an additional sensor for tsunami early warning systems. GNSS measurements collected aboard a ship can be used as input parameter to algorithms determining the sea spectrum from the ship motion [3][4]. However, these applications are currently restricted to coastal areas, near one or a network of reference stations.

GNSS precise positioning in the oceans is an attractive possibility, which needs to be exploited. Indeed, precise positioning of a moving ship is especially challenging due to the high dynamics of the antenna and the high reflectivity of the water. The capabilities of GNSS for shipborne applications have been extensively investigated and the core of these studies is based on the possibilities to obtain reliable and accurate antenna coordinates and velocities [5]. A wide variety of different approaches to achieve reliable and accurate PVT has been developed in the past.

Carrier phase (CP) measurements are highly precise observations but they are very sensitive to signal obstruction and inevitably affected by an ambiguity which is unknown to the user. The "classical" way to deal with this issue is realtime-kinematic (RTK) approach. Suchlike method is based on double-differenced carrier phase observations from a rover and a base receiver. The method is usually applied to raw data from geodetic grade receivers and is restricted to baseline lengths of about 10 km. Several minutes of static initialization data are required in order to estimate the unknown ambiguities to fixed values.

Precise Point Positioning (PPP) is going to become an efficient alternative to relative kinematic positioning for maritime applications. PPP aims for precise static and kinematic position determination using a single GNSS receiver. The success of this method will significantly improve the operational flexibility of GNSS precise positioning, reducing the field operational costs. Such method will increase the number of applications using GNSS technology, and will play a major role in marine geodesy, offshore surveys and physical oceanography allowing precise positioning in extensive ocean areas where it was not possible before. Applying precise satellite orbit and clock corrections as well as ionospheric correction maps, the method allows to achieve centimeter precision after successful static initialization of typically more than 20 minutes using a stand-alone GNSS receiver [6].

Time-differencing of CP measurements is a way to use

CP, cancelling the ambiguity. The conventional way to compute velocities using a stand-alone GNSS receiver is either by differencing two consecutive positions or by using Doppler measurements relative to user-satellite motion [7]. Doppler-based velocity is the most widely used technique with a cm/s accuracy, while differencing consecutive positions from single point positioning (SPP) yields velocity with an accuracy one order of magnitude larger. Alternatively, velocity can be computed by processing differences of consecutive carrier phase measurements, which enables accuracies at the mm/s level [8]. Generally, the use of CP observable is limited by the resolution of carrier phase ambiguity, but the Time-Differenced Carrier Phase (TDCP) technique overcomes this problem, because the ambiguity, in the case of no cycle slip, is constant and is erased by means of differencing two consecutive carrier phases. The TDCP observables are directly related to the position variation (delta position) and so are suitable to estimate the average velocity between two considered epochs. Differencing two consecutive carrier phases removes or greatly reduces the effects of various common errors between the measurements allowing a very accurate estimation of velocity and displacement.

The aim of this paper is to compute vertical position variations using two GNSS techniques, both based on CP, such as TDCP and PPP. To this purpose, data from a single frequency (SF) GNSS receiver are processed. The performance of the considered approaches are verified using a static data collection of 4 hours.

II. GPS SINGLE FREQUENCY POSITIONING MODEL

A. TDCP

The TDCP method uses as measurements the single differences in time of the carrier phase measurements, whose equation is given by:

$$\Phi_f = d + c\delta t_r - c\delta t_s - \delta I + \delta T + +\lambda_f N_f + \varepsilon_{\Phi_f} \quad (1)$$

where Φ_f is the measured CP (expressed in m) on the considered frequency *f*, the indices r and s are referred, respectively, to receiver and satellite. The satellite-receiver distance (m) is indicated by d, *c* is the speed light (m/sec), δt_r and δt_s are the receiver and satellite clock offset (sec), δI is the ionospheric delay, δT is the tropospheric delay (m), λ_f is the wavelength of the carrier, N is the phase ambiguity term (in cycles) and ε_{Φ_f} includes multipath and receiver noise.

Computing the time-difference of successive carrier phases to the same satellite at small sampling intervals (≤1 Hz), the TDCP measures are obtained. So, the constant integer ambiguities are eliminated as well as most of the common errors such as satellite clock bias, ephemeris error, tropospheric error, and ionospheric error, which vary slowly within a small interval [8]. The expression of TDCP observations at two successive epochs t_j and t_{j-1} is:

$$\Delta\Phi = \left[\Phi(t_j) - \Phi(t_{j-1})\right] = = \Delta d + c\Delta\delta t_u + c\Delta\delta t_s + \Delta\delta d_{eph} - \Delta\delta d_{iono} + \Delta\delta d_{trop} + \Delta\eta \quad (2)$$

where Δ denotes the differencing operation. The integer ambiguity is not included in Eq. (2) as long as a cycle slip does not occur. TDCP is sensitive to a cycle slip; if it occurs, velocity errors of several cm per seconds can be obtained. To overcome this problem, a technique for the detection and repair of cycle slip should be applied before differencing two consecutive carrier phases. Furthermore, to obtain precise velocity estimation, the errors have to be mitigated. Indeed, the individual carrier phase measurements have to be compensated; corrections for satellite clock error are extracted from broadcast ephemeris while the Klobuchar and Saastamoinen models [8] are applied to mitigate, respectively, the influence of ionospheric and tropospheric effects [9], [10]. In this way, $c\Delta\delta t_s$, $\Delta\delta d_{iono}$ and $\Delta\delta d_{trop}$ terms become time-differences of residual errors and are negligible; $\Delta\delta d_{eph}$ is negligible too in case the ephemeris errors remain quasi constant between the two consecutive epochs considered.

Therefore, the compensated TDCP measurement is:

$$\lambda\Delta\widetilde{\Phi} = \Delta d + c\Delta\delta t_u + \Delta\varepsilon \quad (3)$$

where $\Delta\varepsilon$ includes the errors relative to multipath and receiver noise, and the residuals of the partially corrected error sources.

For the representation of the geometric range change between two epochs, Δd, the approach in [8][9] is considered and its final expression, is given as:

$$\Delta d = \Delta D - \Delta g - \left[\underline{e}(t_j) * \underline{\Delta r_u}\right] \quad (4)$$

where

$$\Delta g = \left[\underline{e}(t_j) * \underline{r_u}(t_{j-1})\right] - \left[\underline{e}(t_{j-1}) * \underline{r_u}(t_{j-1})\right] \quad (5)$$

and

$$\Delta D = \left[\underline{e}(t_j) * \underline{r_s}(t_j)\right] - \left[\underline{e}(t_{j-1}) * \underline{r_s}(t_{j-1})\right] \quad (6)$$

with

$$\underline{e}(t_j) = \frac{\underline{r_s}(t_j) - \underline{r_u}(t_j)}{\left\|\underline{r_s}(t_j) - \underline{r_u}(t_j)\right\|}, \quad \underline{e}(t_{j-1}) = \frac{\underline{r_s}(t_{j-1}) - \underline{r_u}(t_{j-1})}{\left\|\underline{r_s}(t_{j-1}) - \underline{r_u}(t_{j-1})\right\|} \quad (7)$$

being the line of sight unit vectors, and $\underline{a}*\underline{b}$ being the inner product of vectors $\underline{a}$ and $\underline{b}$, $\underline{r_s}$ is the satellite position vector, $\underline{r_u}$ is the receiver position vector; $\underline{\Delta r_u}$ is the receiver position change (delta position), which is proportional to the average receiver velocity between epochs t_j and t_{j-1} The term Δg takes into account changes in the relative satellite-receiver geometry that occur because the line of sight vector changes its orientation; the term ΔD represents a change in the range and is proportional to the average Doppler frequency shift caused by satellite-receiver relative motion along the line-of-sight [8][9].

The TDCP measurement compensated and adjusted for the terms ΔD and Δg becomes:

$$\lambda\Delta\tilde{\Phi}^{adj} = \lambda\Delta\tilde{\Phi} - \Delta D + \Delta g = \\ = -\left[\underline{e}(t_j) * \underline{\Delta r_u}\right] + c\Delta\delta t_u + \Delta\varepsilon \quad (8)$$

Assuming m equations ($m \geq 4$) like (8), it is possible to solve for the unknowns $\underline{\Delta r_u}$ and $c\Delta\delta t_u$ using the Weighted Least Squares (WLS) method as detailed in [8], [11]; the weights of the weighting matrix are chosen related to the elevation of the satellites [12].

Furthermore, the classic broadcast ephemeris selection criterion cannot be used for TDCP. Usually, the broadcast ephemeris set closest to the measurement epoch is chosen to compute position with pseudoranges or velocity with Doppler measurements. In this way, it can happen that two different ephemeris sets are used at two certain consecutive epochs. Conversely, the TDCP technique requires two consecutive measurements and the use of different broadcast ephemerides can give rise to a discontinuity in the TDCP measurements, affecting the velocity estimation. This limit can be overcome computing satellite positions using the same broadcast ephemeris set at epochs t_j and t_{j-1} [8].

B. SF-PPP

SF-PPP is based on pseudorange (PR) and CP observations and their equations, at frequency *f*, are:

$$PR_f = d + c\delta t_r - c\delta t_s + \delta I + \delta T + K_{PR_f,r} \\ - K_{PR_f,s} + \varepsilon_{PR_f} \quad (9)$$

$$\Phi_f = d + c\delta t_r - c\delta t_s - \delta I + \delta T + k_{\Phi_f,r} \\ - k_{\Phi_f,s} + \lambda_f N_f + \lambda_f w \\ + \varepsilon_{\Phi_f} \quad (10)$$

where PR_f is the measured PR (in m) for the frequency *f* and Φ_f is the measured CP (expressed in m) on the considered *f*. The terms d, δt_r and δt_s, δI, δT i λ_f, N have the same meaning of eq. 1. In addition, $\lambda_f w$ is the windup term due to the circular polarization of the electromagnetic signal. The terms $K_{PR_f,r}$ and $K_{PR_f,s}$ are the receiver and satellite instrumental delay for the code measurements, while $k_{\Phi_f,r}$ and $k_{\Phi_f,s}$ are the CP instrumental delay. Finally, ε_{PR_f} and ε_{Φ_f} contain the residual error for the PR and CP measurements [13][14].

The core of the PPP is the use of several correction models to be applied to mitigate the errors and biases affecting the measurements, such as: the precise IGS final orbit and satellite clock corrections; GIM from the CODE for the ionospheric delay and Saastamoinen's hydrostatic delay correction is used for the computation of the tropospheric zenith dry delay [14]. The wet component of the tropospheric zenith delay (zpd_w) is considered as an additional unknown parameter in the estimation process [14]. Differential Code Biases (DCB) are downloaded by CODE to correct the satellite instrumental delays while code and phase receiver instrumental delay will be adsorbed into the receiver clock and phase ambiguity terms, respectively. Finally, effects of CP windup, satellite antenna offsets, ocean tide loading and relativity are also corrected [14].

Applying the described corrections, the SF-PPP observation model considering GPS system is obtained:

$$\widehat{PR}_{C1} = d + c\widehat{\delta t_r} + m_r\, zpd_w + \varepsilon_{PR} \\ \hat{\Phi}_{L1} = d + c\widehat{\delta t_r} + m_r\, zpd_w + \lambda_{L1}\hat{N}_{L1} + \varepsilon_{\Phi} \quad (11)$$

where, $\widehat{PR}$ and $\hat{\Phi}$ are the corrected PR and CP observables, C1 denotes C/A code on L1 GPS signal,. The zpd_w term is the wet part of the tropospheric delay and m_r^* is the troposphere mapping function; c is the speed light, $\widehat{\delta t_r}$ is the combined effect of the receiver clock error and the receiver code hardware delay, $\hat{N}$ is the ambiguity parameter joined to the CP instrumental delays; ε_{PR}^*, ε_{Φ}^* are the noise terms [14].

After the linearization around approximate values of the unknowns, the SF-PPP measurement model expressed in matrix form is:

$$\underline{z} = H\underline{\Delta x} + \underline{\varepsilon} \quad (12)$$

where $\underline{z}$ is the measurements vector containing the difference between the measured and predicted observables, $\underline{\Delta x}$ are the increments to the approximate solution, H is the design matrix and $\underline{\varepsilon}$ is the vector of the residual errors.

The unknown parameters in SF-PPP are the receiver coordinates, the biased receiver clock error, the wet component of the tropospheric delay and the non-integer ambiguity parameters. The ambiguities are estimated as real numbers by the chosen filter, so they are called floating ambiguities. For the SF-PPP solution computation, at least 5 satellites are necessary since the numbers of equations is 2m and the unknown parameters are m+5 [14].

The unknown parameters are estimated by the Extended Kalman filter, as explained in [15]. Furthermore, to apply the KF method, the stochastic models of both measurements and parameters need to be defined. A variance model as function of the satellite elevation is used for PRs while the variance of CP is empirically scaled by a 1/100 factor. Finally, the stochastic model of the unknown parameters is chosen as detailed in [14].

III. TEST AND RESULTS

To verify the performance of the proposed algorithms and their effectiveness to compute the altitude variations (Delta U), a static data collection of four hours is considered. Measurements, with a sample rate of 1 Hz, have been downloaded from ZIMM station of IGS network, located in Zimmerwald (Switzerland), at the 29th of January 2019. The test is static, so the antenna is placed in a well-known location and its velocity is zero.

The operational scenario emerges from the analysis of satellite visibility and geometry, shown in fig. 1 where the total number of visible GPS satellites and the behaviour of the Position Dilution of Precision (PDOP) are plotted. The number of GPS satellites varies from 0 to 9, with an average of about 8. During the observation period, PDOP varies from a minimum value of 1.5 to a maximum of 2.9 with an average of 2.1.

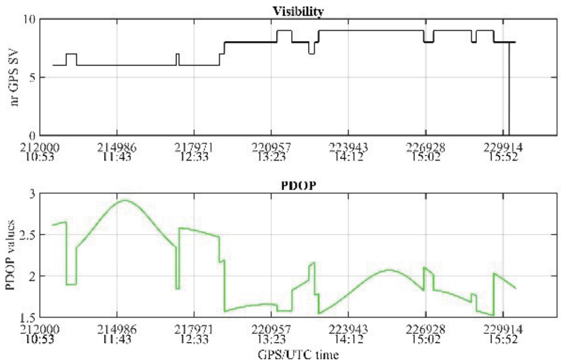

Fig. 1 GPS satellites availability and PDOP values during the data collection.

The data have been processed using SF-PPP and TDCP algorithms and the performance analysis is conducted comparing the time history of the vertical component of the TDCP solution versus the SF-PPP vertical variation computed between consecutive epochs.

The altitude variations computed using TDCP have a mean value of circa 0.49 mm and a RMS of circa 4.7 mm. Conversely, the vertical variations computed using SF-PPP have a RMS of 6.9 mm and the mean value is very near to zero (0.0015 mm). The highest value is obtained using the SF-PPP at the beginning of the data collection when the solution is not stable. This period, named time convergence, is due to the estimation of the floating ambiguities that need about 90 minutes.

The variation of the vertical component computed using the two approaches are plotted as function of the time in the fig. 2 where the blue line represents the TDCP vertical displacements behaviour and the orange line refers to SF-PPP. The altitude variations greater than 10 cm obtained using SF-PPP are not shown in the figure.

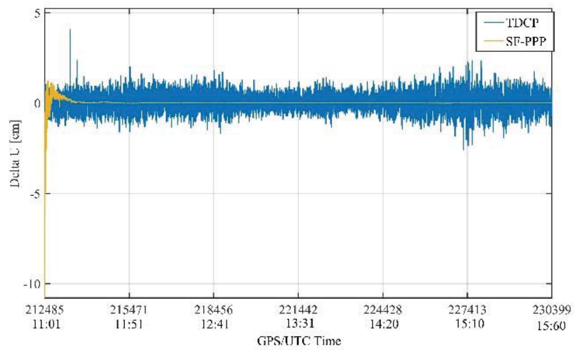

Fig. 2 Time history of delta heights computed using TDCP (blue line) and SF-PPP (orange line) approaches.

The figure confirms that the best result is obtained using SF-PPP that gives altitude variations more stable and near to zero with respect to TDCP.

IV. CONCLUSIONS

The paper compares the performance of two approaches to compute vertical position variations using a single frequency stand-alone GPS receiver. The considered techniques are time-differenced carrier phase (TDCP) and precise point positioning (PPP), both based on the use of the precise CP measurements.

PPP is a well-known GNSS processing technique providing decimeter to-centimeter positioning accuracy without the use of corrections from reference stations but using precise satellite products and error correction models. However, the existing SF-PPP methods can be hardly implemented for high-precision applications due to the large error sources that affect accuracy and converge time of navigational solution. For instance, since SF- PPP is fundamentally based on float solutions, the ambiguity term needs more time for the solutions to stabilize, influencing the convergence behaviour. Furthermore, during the convergence period, the floating ambiguities may also limit the accuracy and precision of the SF-PPP solutions during the initial observation time as shown by the obtained results. Indeed, fig. 2 shows a convergence time of 90 minutes where there are the highest PPP errors. So, the long convergence time becomes the limiting factor for the use of SF-PPP techniques for real-time applications.

On the other hand, TDCP technique overcomes the problem due to the resolution of carrier phase ambiguity, removing the ambiguity by means of differencing two consecutive carrier phases when no cycle slips occur.

The performance of the two techniques are analysed using a static data collection of 4 hours and the results have demonstrated that both methods can provide millimetre accuracy in an open sky scenario. In particular, at the beginning of the data collection TDCP vertical variations are lower than SF PPP ones that are affected by the floating ambiguities. Conversely, after the convergence time the SF

PPP solutions are very near to zero and more stable than TDCP.

In conclusion, a combination of the two approaches can provide a potential and promising technique for precise kinematic positioning of remote marine platforms in open oceans and their performance can be improved using multi-GNSS constellation.

ACKNOWLEDGMENT

This research is supported by funding for basic activities related to research (FFABR) introduced by Law no. 232/2016.

REFERENCES

[1] IOC - International Oceanographic Commission, “Manual on seal level measurement and interpretation”, vol. IV, JCOMM technical report No 31, UNESCO, 2006.

[2] IHO, Manual on Hydrography, International Hydrographic Organization, Publication M-13, 1st edition, May 2005.

[3] Marreiros, J.P.R. “Kinematic GNSS Precise Point Positioning: Aplication to Marine Platforms”. Ph.D. Thesis, University of Porto, Porto, Portugal, 6 June 2013.

[4] Reinking, J., Härting, A., & Bastos, L. “Determination of sea surface height from moving ships with dynamic corrections”, Journal of Geodetic Science, *2*(3), 172-187, 2012.

[5] Gaglione, S., Angrisano, A., Freda, P., Innac, A., Vultaggio, M., & Crocetto, N. “Benefit of GNSS multiconstellation in position and velocity domain” In *2015 IEEE Metrology for Aerospace (MetroAeroSpace)*, pp. 9-14, IEEE.

[6] Gao, Y. “What is precise point positioning (PPP), and what are its requirements, advantages and challenges?” Inside GNSS, 1(8):16–18. ISSN 1559-503X, 2006

[7] Kaplan E. D., Hegarty J. “Understanding GPS: Principles and Applications 2th edn”. Artech House, Norwood, Massachusetts, 2006

[8] Freda, P., Angrisano, A., Gaglione, S., & Troisi, S. “Time-differenced carrier phases technique for precise GNSS velocity estimation”. *GPS Solutions*, *19*(2), 335-341, 2015.

[9] Van Graas F., Soloviev A. Precise Velocity Estimation Using a Stand-Alone GPS Receiver”. Proc. ION NTM 2003, Institute of Navigation, Anaheim, California, 22-24 January, 283-292, 2003

[10] Angrisano, A., Gaglione, S., Gioia, C., Massaro, M. and Robustelli, U., “Assessment of NeQuick ionospheric model for Galileo single-frequency users”. *Acta Geophysica*, *61*(6), pp.1457-1476, 2013.

[11] Gaglione, S., Angrisano, A., Pugliano, G., Robustelli, U., Santamaria, R. and Vultaggio, M., “A stochastic sigma model for GLONASS satellite pseudorange." Applied Geomatics, 3(1), pp.49-57, 2011.

[12] Crocetto, Nicola, et al. "Fuzzy-logic based methodologies for mobile mapping: Enhancing positioning accuracy of gps/gnss measurements."*The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 36 (2007).

[13] J. Sanz Subirana, J.M. Juan Zornoza & M. Hernandez-Pajares, “GNSS Data Processing, Vol. I: Fundamentals and Algorithms”, *ESA communications, ESTEC TM-23/l, Noordwijk, the Netherlands*, 2013.

[14] Innac, A., Gaglione, S., & Angrisano, A. “Multi-GNSS Single Frequency Precise Point Positioning”. Presented at the *2018 IEEE International Workshop on Metrology for the Sea*, 8-10 October, Bari, Italy.

[15] Rabbou, M. A., & El-Rabbany, A. “An Improved GPS/GLONASS PPP Model for Kinematic Applications.” *J. Arab Inst. Navigation–AIN J.*, *32*(1)., 2015