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Position Domain analysis of modernized GPS Ionosphere-free Code Observations

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Abstract

New signals (L2C and L5) are added as a part of GPS modernization to improve the achievable accuracy of the system. Compared to the legacy signals (L1/L2), new signals provide good cross-correlation performance, Forward Error Correction (FEC) and tracking facility. But the systematic errors in range measurements are the concern, particularly due to the ionospheric delay. The ionosphere-free linear combinations of dual frequency code or carrier phase measurements can be used to correct the refraction effects on GPS signals. The availability of L2C and L5 on Block-IIRM satellites has given an opportunity of direct comparison of coded signals instead of carrier-phase measurements. Simulation studies in the open literature on optimal linear combinations are focused in measurement domain. The analysis in respect of precision on coordinate parameters is essential to realize the optimal linear combination in position domain. Two ionosphere-free linear combinations L1/L5 and L2C/L5 of undifferenced/zero-differenced GPS coded signals are investigated for Single Point Positioning (SPP).

1. Introduction

Modernization of GPS is in progress by providing services through new civilian signals such as L5 and L2C along with Military codes on L1 and L2 signals. The L5 signal is the third civilian signal, after L1C/A and L2C. These three civilian signals can be used for Standard Positioning Services (SPS) by all the GNSS users worldwide for free of cost. Correcting for ionospheric error is a significant challenge to improve the positional accuracy. Either code-phase or carrier phase measurement on different frequencies can be combined to compensate for ionospheric delay. The undifferenced pseudorange/code-phase observables can be processed to obtain Single Point Position (SPP) solution.

Extensive research by Cocard and Geiger [1], Han and Rizos [2], Odjick [3] and Richert [4] outlines the criteria for optimal linear combinations using dual and triple frequency carrier phase measurements. However, the focus is into the measurement domain but not in the position domain. Also in case of triple frequency most of the research reported is based on simulated of signal measurements. In critical applications like Local Area Augmentation systems (LAAS) for category precision landing of aircrafts, code-phase measurements are processed for navigation solution. Therefore, in this paper the undifferenced dual and triple frequency ionosphere-free code-phase linear combinations in position domain are evaluated.

2. Modernized GPS Signals

The satellites from Block-I through Block-IIR transmits C/A-code on L1 frequency and P(Y) code on both L1 and L2 frequencies. However, the new generation of satellite vehicle Block-IIR-M (L2C) and Block-IIF (L5I and L5Q) are under deployment to transmit additional civil signals. In addition to this, for PPS an M-code signal on L1 and L2 frequencies is transmitted to overcome the legacy P(Y) code in terms of accuracy and security. The representation, L2C indicates civil signal on L2 carrier frequency. As the L2C signal belongs to Radio Navigation Satellite Services (RNSS) band, it is not appropriate for civil aviation. On the other hand, L1 and L5 can be used for safety of life applications, as these frequencies belong to Aeronautical Radio Navigation Service (ARNS) band. The L5 signal is the third civilian signal, after L1C/A and L2C. The Block III GPS satellites will have the fourth civilian signal L1C superimposed on L1 carrier in near future. This is a new civil signal that has backward compatibility with L1C/A.

3. GPS principle of operation

The GPS receivers track and acquire afore mentioned signals, and measure ranges to all the satellites in-view to estimate the user's position in 3-D (latitude, longitude and height). Let the user be at xu, yu and zu in earth fixed, earth centered coordinate system and the Satellite Vehicles (SVs) be at xi, yi and zi (where i=1,2,3,4) in the same coordinate system as the user. Fig. 1. depicts principle of operation. Assuming that the user starts his clock at tu seconds, receives signals at ti (i=1, 2, 3, 4) seconds from SV and Δt is the time offset between the user and SV. 3D position and time offset are obtained by simultaneously solving the nonlinear equations [5],

$$(x_u - x_i)^2 + (y_u - y_i)^2 + (z_u - z_i)^2 = c(t_i - t_u + \Delta t)^2 \tag{1}$$

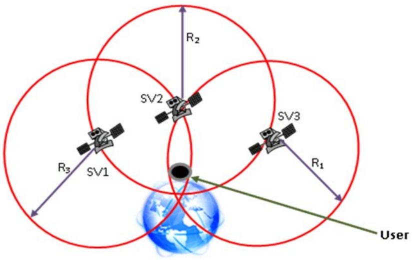


Figure 1 GPS Positioning using three satellites

4. Linear combinations

By developing various Linear Combinations (LC) of multi-frequency phase or code data an optimal pseudo observation can be derived. The optimal combination will also aid in elimination or mitigation of GPS errors such as ionospheric error, multipath etc. Several linear combinations are proposed using GPS L1/L2 data. The various linear combinations are, narrow-lane, ionosphere-free, wide-lane, semi-wide-lane, and geometry-free combinations etc., [6]. The present study is only on ionosphere-free combination and its impact on position solution. other linear combinations of GPS data are out of scope of this paper.

4.1 Ionosphere-free linear combination

The effect ionosphere is eliminated by using this linear combination. This is widely used for smoothing of code measurements to reduce the effect of noise and multipath as well. The ionosphere-free linear combination using un-differenced or zero-difference L1-L2C and L1-L5 code measurements can be written as [7],

$$R_{If_{L2/L5}} = \frac{1}{f_{L2}^2 - f_{L5}^2}(f_{L2}^2.R_2 - f_{L5}^2.R_5) \qquad (1)$$

$$R_{If_{L1/L5}} = \frac{1}{f_{L1}^2 - f_{L5}^2}(f_{L1}^2.R_1 - f_{L5}^2.R_5) \qquad (2)$$

where,

R_1: Pseudorange on L1 (m), R_2: Pseudorange on L2C (m), R_5 :Pseudorange on L5 (m), $R_{If_{L1/L5}}$: Ionosphere-free pseudorange of L1-L5, $R_{If_{L2L5}}$: Ionosphere-free pseudorange of L2C-L5.

5. Position Error

There are three different approaches to describe position error such as formal accuracy, predicted accuracy and measured accuracy. The formal errors rely on statistical characterization of errors and linear model used for position estimation. This gives the uncertainty of the error estimates but not the actual error. The predicted accuracy is based on satellite-receiver geometry and involves calculations using only standard deviation of measurements by evaluating Dilution of Precision (DOP) parameter. Whereas, actual range measurements are used to assess accuracy of position estimate in local coordinates (East, North, UP (ENU)) in case of measured error. The error in ENU coordinates are assessed using above discussed linear models of ionosphere-free linear combinations. The root-mean-square vertical and horizontal (2-D) and 3D errors are analyzed to determine the measured accuracy of ionosphere-free linear combination of GPS signals and expressed as [8],

$$2D - RMS\ horizontalerror = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta E_i^2 + \Delta N_i^2)^2} \qquad (2)$$

$$RMSverticalerror = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\Delta U_i^2} \qquad (3)$$

$$3D - RMS\ error = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta E_i^2 + \Delta N_i^2 + \Delta U_i^2)^2} \qquad (4)$$

6. Experimental setup and data acquisition

A multi-frequency GNSS receiver (Model: PolaRxs pro, make: Septentrio, NV) capable of tracking GPS, GlONASS, Galileo and SBAS (WAAS, GAGAN, EGNOS) satellite signals was setup at Geethanjali College of Engineering and Technology (GCET), Hyderabad. Fig.1. depicts the experimental setup.

Figure 1. Septentrio PolaRxs-Pro GNSS receiver and antenna setup at GCET, Hyderabad

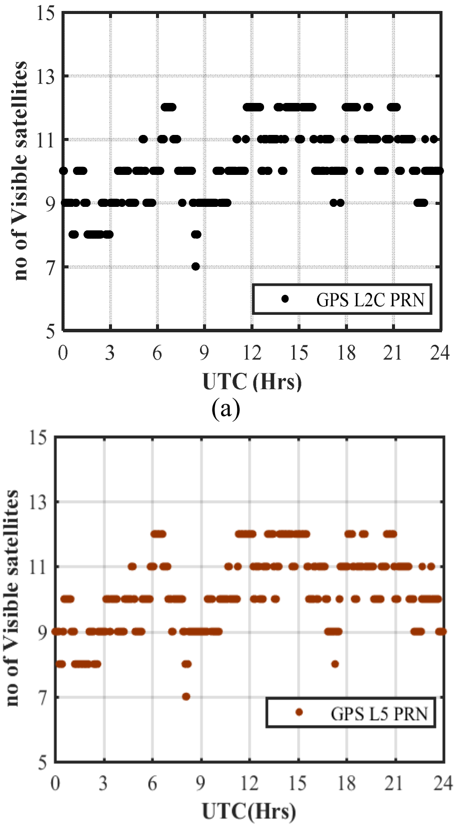
The receiver was connected to HP workstation for continuous data acquisition. The raw data is recorded in SBF format and are converted to Rinex 2.1version using the software provided by the manufacturer. The two files observation file and navigation file are obtained for analysis. Two days data of month September 28-29, 2018, with sampling interval of 15s is used in the analysis.

7. Methodology

To estimate the position, dual frequency ionosphere-free linear combination of code-phase are used rather using single frequency carrier/code phase measurements. Brancroft method and Kalman filter techniques are applied with the pseudorange due to ionosphere-free combination of observations. These measurements are corrected for other error sources orbit (considering precise orbits), satellite and receiver clock bias and troposphere. The absolute error in position estimation is computed for the linear combinations of GPS stand alone for (L1C/A – L5) and (L2C - L5)

6. Results and discussion

The current status of GPS constellation has 32 satellites. Among them only 19 satellites (PRN: 01, 03, 05, 06, 07, 08, 09, 10, 12, 15, 17, 24, 25, 26, 27, 29, 30, 31, 32) are with L2C capability and 12 satellites (PRN: 01, 03, 06, 08, 09, 10, 24, 25, 26, 27, 30, 32) with L5 capability. The visibility of the satellite at GCET site for a typical day (DoY:271, 28th September 2018) is depicted in Fig.2.



(a)

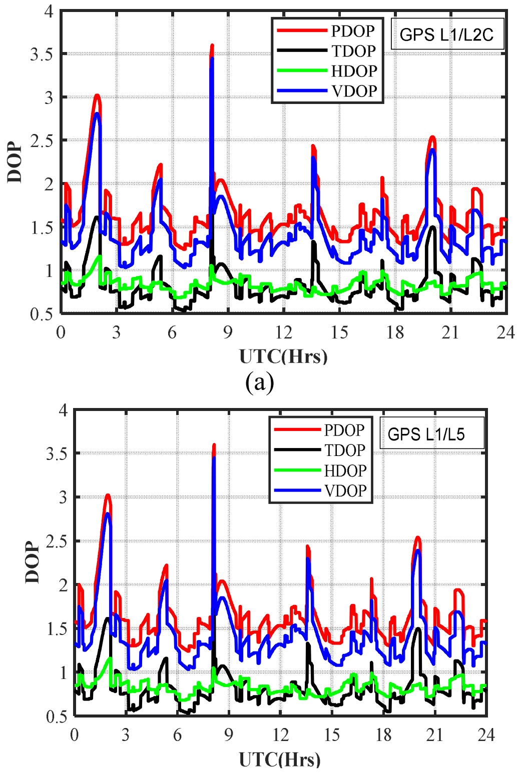
(b)

Fig.2 GPS satellites visible at GCET (a) With GPS L2C capability and (b) With L5 capability

It is evident that a minimum of 7 and maximum of 12 are visible with L2C and L5 capability. The satellite geometry, dilution of precision for the current scenario with only modernized signals is depicted in Fig.3.

It can observed that there no much difference in DOP values because of the satellite visibility in either the case. The maximum PDOP noticed is about 3.5 and minimum is about 1.24.

The position estimation due to the ionosphere-free combination of modernized GPS observations is performed by evaluating measured error in local coordinate systems (east-north-up (ENU)). Eq.2-4 are used to determine the accuracy and precision of estimated position.



(a)

(b)

Fig.3 Epoch wise DOPs for visible satellites of (a) GPSL1-L2C and (b) GPS L1-L5 linear combination of observations

Table 1 and 2 depicts minimum, maximum and mean values of various DOPs with respect to the plot in Fig.3.

Table 3 Minimum, Maximum, Mean and Standard deviation of DOPs of GPS L1-L2C

DOPs	Min.	Max.	Mean	Std.
HDOP	0.65	1.12	0.81	0.09
VDOP	1.05	3.40	1.40	0.36
PDOP	1.20	3.52	1.62	0.37
TDOP	0.60	1.98	0.84	0.25

Table 4 Minimum, Maximum, Mean and Standard deviation of DOPs of GPS L1/L5

DOPs	Min.	Max.	Mean	Std.
HDOP	0.68	1.16	0.82	0.07
VDOP	1.03	3.45	1.41	0.34
PDOP	1.24	3.60	1.64	0.32
TDOP	0.53	2.15	0.81	0.21

Figs.4-5 depicts horizontal and vertical error distribution in ENU coordinates.

The descriptive statics minimum, maximum and mean error in ENU coordinates of Fig.4 and 5 is depicted table 5.

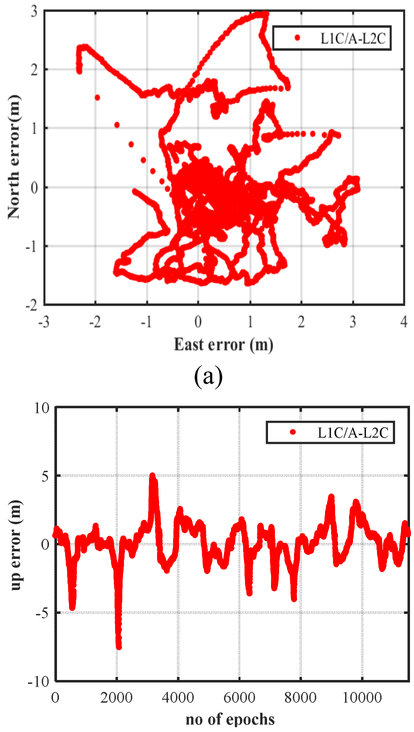
Table 5 Descriptive statistics of position error along east, north and up axes

Linear Combination	East error		North error		Up error	
	Min (m)	**Max (m)**	**Min (m)**	**Max (m)**	**Min (m)**	**Max (m)**
GPS L1C/A-L2C	-2.32	3.10	-1.65	2.79	-7.55	4.99
GPS L1C/A-L5	-2.75	2.76	-2.71	3.42	-4.26	5.74

Table 6 Measured accuracy: RMS vertical, horizontal (2D), and 3D position

RMS position error	**GPS L1C/A-L2C**	**GPS L1C/A-L5**
RMS vertical error (m)	1.40	1.95
2D-RMS horizontal error (m)	2.77	3.59
3D-RMS error (m)	6.34	8.94

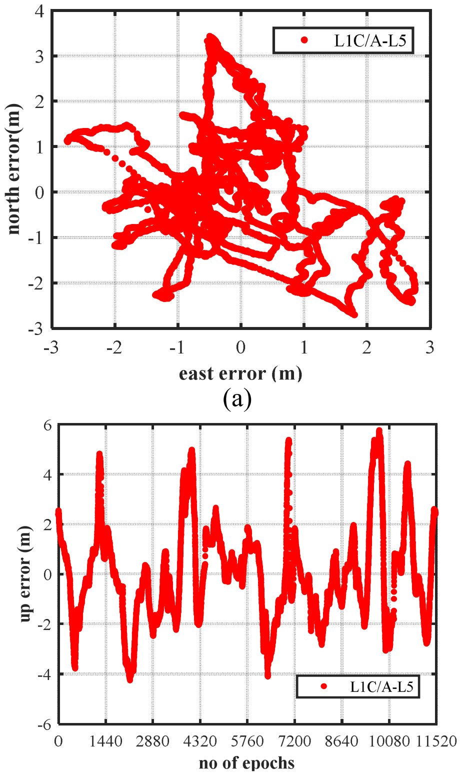
The 95th percentile horizontal and vertical position accuracy is observed to be more for L1-L2C combination as depicted in table 6. The 2-D RMS error is about 2-4meters due to code-phase ionosphere-free combination of modernized GNSS signals. The 3D-RMS position error is about 8.9m and 6.3m for L1-L5 and L1-L2C respectively.



(a)

(b)

Fig.4 Position error for GPS L1C/A-L2C
(a) Horizontal error and (b) Vertical error



(a)

(b)

Fig.5 Position error for GPS L1C/A-L5
(a) Horizontal error and (b) Vertical error

8. Acknowledgements

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9. References

[1]. Cocard, M., and A. Geiger (1992). “Systematic Search for all Possible Widelanes.” Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning, Columbus Ohio March 17-20, 1992, pp. 312-318.

[2]. Han, S., and C. Rizos (1996). "Improving the computational efficiency of the ambiguity function algorithm." Journal of Geodesy, Vol. 70, No. 6, pp330-341.

[3]. Odijk, D. (2003), “Ionosphere-Free Combinations for Modernized GPS”, Journal of Surveying Engineering, Vol.129, No.4, pp.165–173.

[4]. Richert, T., and N. El-Sheimy (2007). “Optimal linear combinations of triple frequency carrier phase data from future global navigation satellite systems.” GPS Solutions, Vol. 11, No. 1, pp. 11-19.

[5]. Bancroft, S. (1985), “An Algebraic Solution of the GPS Equations”, IEEE Transactions on Aerospace and Electronic Systems 21, 1985, pp.56-59.

[6]. Urquhart L. (2009), “An Analysis of Multi-Frequency Carrier Phase Linear Combinations for GNSS”, Senior Technical Report, Depart. of Geodesy and Geomagnetics Engineering, Technical Report, No.263, University of New Brunswick, Fredericton, New Brunswick, Canada, 2009.

[7]. Wenting He, and Qi Zhao (2009), “Research and Implementation of the Modernized GPS Signal L2C and L5”, IEEE Int. Conf. on Computer and Electrical Engg.

[8]. Sanz Subirana J, J.M. Juan Zornoza and M. Hernández-Pajares, “GNSS Data Processing: Fundamental and Algorithms”, Vol.1, May 2013.