Code-phase based combined GPS-Galileo positioning using Ionosphere-free linear combination

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Abstract

To reduce the uncertainty in location information supplied by GNSS receiver, the range errors (clock bias, troposphere, ionosphere, multipath etc.,) have to be eliminated. The linear combinations of multi-frequency GNSS observables, will aid in eliminating most of the errors. The ionospheric error is treated as predominant error and can be mitigated by using ionosphere-free linear combination. In this paper, the attainable accuracy using ionosphere-free linear combination of combined GPS L11/L5 and Galileo E1/E5a is evaluated for single point positioning. Taking the advantages of availability of civilian codes on signal frequencies, code-phase measurements are used instead of carrier-phase. The 95th percentile horizontal, vertical and 3D position accuracies are 1.08m, 0.80m and 1.81m respectively

1. Introduction

The reliability of GNSS range measurements are degraded due to systematic errors or biases and random noise as well. Therefore, pre-processing, processing, analysis and proper interpretation of measurement data is required for achieving optimal navigation solution. The issues addressed in pre-processing include cycle slip detection and repair, ambiguity resolution and code smoothing. The mitigation and modelling of biases and systematic errors in measurements comes under processing. Several algorithms using single, double and triple difference techniques are developed with various linear combinations of dual frequency data for static and kinematic applications. The common limitation among these techniques is that, they depend on the baseline distance between the pair of receivers involved for processing the data. Apart from differencing techniques, new observable can be derived from the basic GNSS observations of multi-frequency, such that new signals can be generated with various with unique properties capable of eliminating GNSS errors and this is achieved using linear combinations [1]. In the present study the ionosphere-free linear combination in position domain for dual system (GPS and Galileo) is investigated.

2. GNSS signal characteristics

The modernization of GPS and upcoming Galileo provide open services with new civilian codes on the following three radio frequencies L1/L2/L5 and E1/E5a/E5b respectively. The wavelengths of these signals are in between 19-25 cm. The frequencies of the signals are L1 L1(1575.42 MHz), L2 (1227.60MHz) and L5 (1176.45 MHz) and in case of Galileo E1(1575.42 MHz), E5a (1176.45 MHz), E5b (1207.14 MHz). These carrier frequencies are Bi-phase modulated in GPS and BOC modulated in Galileo system, by spread spectrum codes with a unique PRN sequence associated with each satellite vehicle (SV) and by the navigation data [2]. The dual mode GPS/Galileo with open service signals will enhance robustness of the navigation solution. Even in future, the dual frequency GBAS system can be deployed and get benefited from these new signals. Therefore, an attempt is made to evaluate the dual mode GPS/Galileo positioning using L1/L5 and E1/E5a signals.

3. Linear combinations

Developing various linear combinations of multi-frequency phase or code data, an optimal pseudo observation can be derived. The optimal combination will aid in elimination or mitigation of GNSS errors. 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. The systematic errors eliminated using a specific linear combination can be found in open literature [3].

In particular, with ionosphere-free linear combination, most of the analysis carried out is mostly in measurement domain and not in position domain. The advantage of using linear model is that it can be directly in least squares adjustment to obtain position solution and eliminates using of a particular ionospheric model. Because, though Global, regional and local ionospheric models are being developed for supporting GNSS systems worldwide. The spatial and temporal resolution of these models is limited and major error still remains at times of high solar activity periods.

3.1 Ionosphere-free linear combination

This linear combination eliminates the effect of ionosphere. This is widely used in time and frequency transfer applications as well. The noise in the derived measurements is less. The possible ionosphere-free combinations using GPS frequencies can be found in open literature [3]. The ionosphere-free linear combination or pseudorange (($R_{If_{L1/L2}}$) of GPS and Galileo dual frequency code measurements is expressed as,

$$R_{If_{L1/L2}} = \frac{1}{f_{L1}^2 - f_{L2}^2}(f_{L1}^2.R_1 - f_{L2}^2.R_2) \quad (1)$$

$$R_{If_{E1/E5a}} = \frac{1}{f_{E1}^2 - f_{E5a}^2}(f_{E1}^2.R_1 - f_{E5a}^2.R_{5a}) \quad (2)$$

Where,
R_1: Pseudorange on L1 (m) on L1/E1
R_5:Pseudorange on L5 (m) on L5/E5a,
The coefficients for E1.(1) are 2.2606 and 1.2606 for the case of GPS. In Eq.(2) for Galielo frequencies 2.2606 and 1.2606. as it can be noted L1/E1 and L5/E5 frequencies are same.

4. GNSS positioning and error

The GNSS receivers measure ranges to all the visible satellites to estimate the user's position in 3-D (latitude, longitude and height). The basic principle of positioning is based on trilateration technique using time of arrival (TOA) signals. Considering the time difference (Δt) between the satellite signal transmission 'ti' (i=1, 2, 3, 4) and signal received time in the receiver 'tu'. User (x_u, y_u, z_u) and satellite coordinates (x_i, y_i, z_i) are expressed in be earth fixed, earth centered coordinate system.
3D position and time offset are obtained using Bancroft algorithm and solving for 4 non-linear equations expressed as [4],

$$(x_u - x_i)^2 + (y_u - y_i)^2 + (z_u - z_i)^2 = c(t_i - t_u + \Delta t)^2 \quad (3)$$

With sufficient number of satellite (minimum 4) a least square solution solves the normal equation for first position fix. Kalman filter is further used to smooth least square solution to improve precision.
However, apart from the systematic errors, position error also depends on satellite geometry i.e., Dilution of precision (DOP), which is a multiplicative factor and unit less quantity. DOP significantly reduces, with the availability of more satellites.

Position error = user range error ×DOP (4)

Computation of DOP and details of various DOP that determine horizontal, vertical and position DOP (Viz. HDOP, VDOP and PDOP) can found elsewhere [5].
Next coming to positional accuracy, three methods are used to determine error in estimated position formal accuracy, predicted accuracy and measured accuracy. Formal and predicted accuracy quantify the uncertainty of the error. Measured accuracy gives absolute error in position. Therefore, in this paper measured accuracy is used in determining 2D horizontal and vertical error and 3D position error using the below equations [6],

$$2D - RMS\ horizontalerror = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta E_i^2 + \Delta N_i^2)^2} \quad (5)$$

$$RMSverticalerror = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\Delta U_i^2} \quad (6)$$

$$3D - RMS\ error = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta E_i^2 + \Delta N_i^2 + \Delta U_i^2)^2} \quad (7)$$

5. Methodology

Dual frequency ionosphere-free linear combination of code-phase measurements 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 also corrected for other error such as orbit (by considering precise orbits), satellite and receiver clock bias and troposphere. The absolute error in position estimation is computed dual system (GPS (L1C/A - L5) and Galileo (E1-E5a) combined).

6. Experimental setup and data

Experimental investigations have been carried out utilizing the multi-frequency GNSS receiver (make Septentrio, Nv Model: PolaRxs pro) capable of tracking GNSS (GPS, GlONASS, Galileo) and SBAS (WAAS, GAGAN, EGNOS) located at Geethanjali College of Engineering and Technology (GCET), Hyderabad, India is used (Fig.1). The data with sampling interval of 15s is considered for the analysis. Data collected between two days (28th and 29th, September 2018) has been utilized to evaluate the performance combined GPS-Galileo positioning for single point positioning (SPP).

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

7. Results and Discussions

The present GPS constellation has 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:272) are depicted in Fig.2 for GPS L1/L5 combination of observations. Fig.2 depicts a minimum of 7 and maximum of 12 satellites visible, over a period of 24 hours.

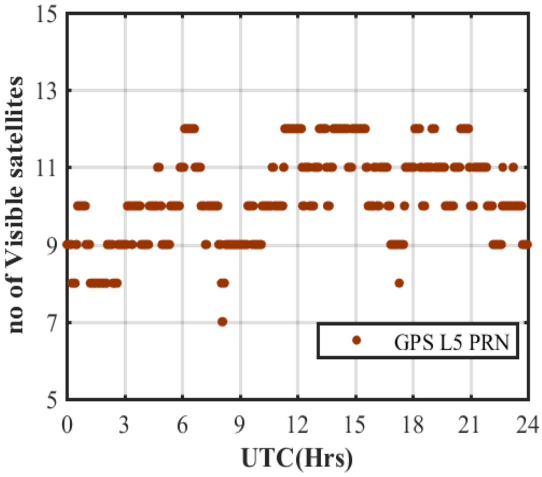


Figure 2 GPS L5 Satellites Visibility at GCET

The availability of satellites increased when satellites of dual system (GPS+Galileo) is considered. A minimum of 10 and maximum of 19 satellites are visible (Fig.3). It is anticipated that the GPS constellation with full L5 operational capability in near future will obviate the need for code less and semi-code less receivers by facilitating receivers with L5 in combination with L1. Therefore, in evaluating the combined GPS-Galileo positioning, L1/L5 combination is used for GPS.

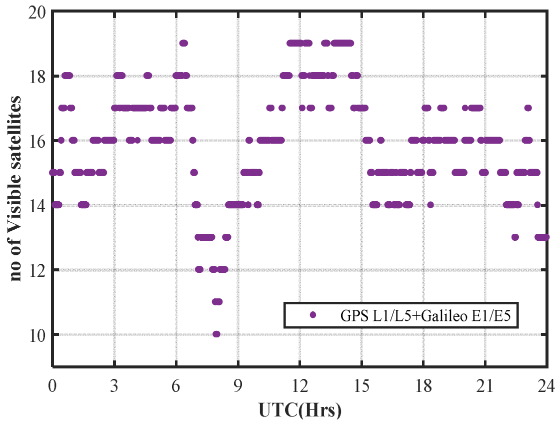


Figure 3 GPS L5 Satellites Visibility at GCET

The satellite visibility is crucial because the DOP is a constrain that limit the attainable positional accuracy and also Positions with a lower DOP generally constitute better measurement. However, combined GPS-Galileo as depicted in Fig.4 shows optimal values.

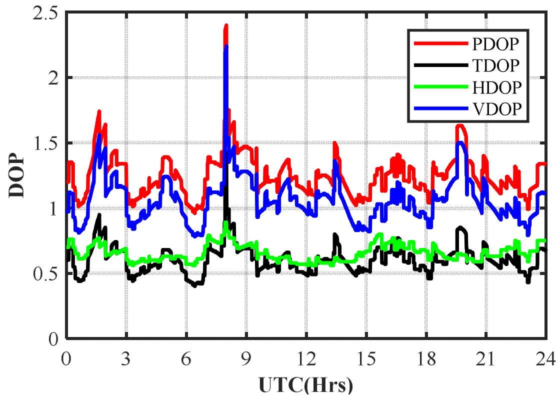


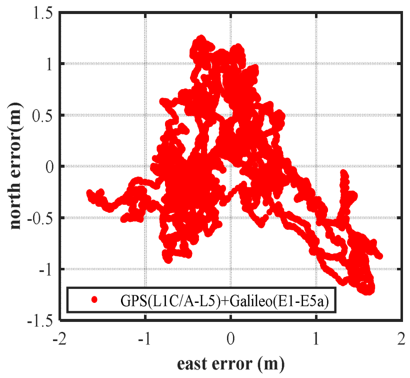
Figure 4 DOPs of GPS-Galileo constellation

DOP values between 1-2 are the most exciting measurement to be met. The minimum, maximum PDOP are 0.96 and 2.40 respectively as can be observed from Fig.4, near optima values. Table 1 shows the minimum, maximum, mean and standard deviation of DOPs for combined GPS+Galileo.

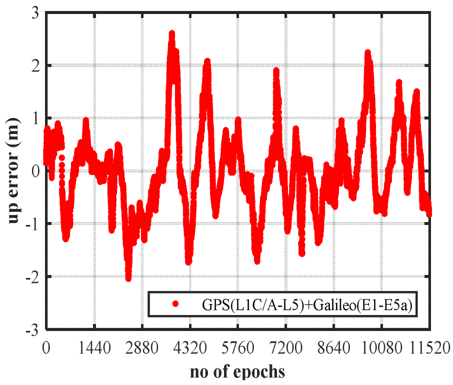
Table 1 Minimum, Maximum, Mean and Standard deviation of DOPs of GPS+Galileo

DOPs	Min.	Max.	Mean	Std.
HDOP	0.56	0.89	0.65	0.06
VDOP	0.78	2.24	1.06	0.17
PDOP	0.96	2.40	1.25	0.16
TDOP	0.40	1.43	0.60	0.11

The error in the estimated position of GNSS receiver is usually described by the terms accuracy and precision. The degree of closeness of an estimate to its true position, which is an unknown value is accuracy and precision is the degree of close of observations to their mean value. The commonly used measures to quantify accuracy and precision are 2D RMS and 3D position error as described by Eq.5-7. Therefore, the position domain analysis is performed by evaluating measured error in local coordinate systems (east-north-up (ENU)) instead of ECEF. The error in estimated position is calculated by taking difference from the average position of 11520 epochs/observations.
The horizontal and vertical position error in ENU coordinates are presented in Fig.5.



(a)



(b)

Fig.5 Position error for dual system (GPS+Galileo) (a) Horizontal error and (b) Vertical error

The descriptive statics are depicted in table 6. The maximum error in east, north and up coordinates are 1.74m, 1.24m and 2.59m respectively when position is estimated using dual system (Table 2).

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

Linear Combination	East error		North error		Up error	
GPS L1/L5 + Galileo E1/E5a	**Min (m)**	**Max (m)**	**Min (m)**	**Max (m)**	**Min (m)**	**Max (m)**
	-1.65	1.74	-1.23	1.24	- 2.0	2.6

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

RMS position error	**GPS L1/L5 + Galileo E1/E5a**
RMS vertical error (m)	0.80
2D-RMS horizontal error (m)	1.08
3D-RMS error (m)	1.84

The 95th percentile horizontal, vertical and 3D position accuracies are 1.08m, 0.80m and 1.81m respectively (Table 3). Table 4 shows the GCET location in ECEF and geodetic coordinates derived from the dual frequency ionosphere-free linear combination using dual-system (GPS+Galileo) measurements.

Table 4 GCET location in ECEF and Geodetic coordinates

ECEF coordinates		**GPSL/L5 and GalilsoE1/E5a**	**Lat./Long./Height**
X (m)		1199419.584	17.521 degrees
Y (m)		5965113.838	78.631 degrees
Z (m)		1908094.934	464.21 meters

8. Conclusions

Combined GPS-Galileo positioning improve the attainable precision and accuracy, which is apparent from the RMS horizontal, vertical and 3D position accuracies. It can be noticed that the positional accuracy is less than 2 meters (Table3) for single point positioning. Presently, the constellation capacity of Galileo is only 14 satellites. Out of which at the site (GCET) a maximum of 9 are only visible. In near future, it can be anticipated that with full operational capacity of Galileo along with more number of GPS L5 satellites the robustness of navigation solution improves. The results are encouraging and may find useful for future implementation of dual frequency Ground Based Augmentation systems (GBAS) as well.

9. Acknowledgements

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