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Assessing Potential Performance of GPS and Galileo in Context of Broadcast Precise Orbits and Clock Corrections

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ABSTRACT

The global navigation satellite system (GNSS) is becoming a vital positioning technology across various services. The ephemeris quality is one of the factors that directly impact the user's position accuracy. Some applications, such as investigations into Earth's crustal dynamics, need more precise ephemeris data than broadcast ephemeris. Several institutions, such as the international GNSS service (IGS), have developed precise orbital services to enable these applications. Unfortunately, data rates for such precise orbits are often confined to 15 minutes. In this paper, in order to generate precise ephemeris with the broadcast sampling period, the well-known Lagrange interpolation method is used. Furthermore, a comparative GPS and Galileo position analysis corresponding to the broadcast and precise ephemeris over a typical day in September 2021 is presented. To get insight into comparative positioning analysis over Hyderabad Station, the ENU (East-North-Up) directional errors, satellite visibility and horizontal accuracy parameters are considered. Based on the numerical analysis, standalone Galileo has similar capabilities to GPS, and it can be used in Multi-GNSS over India and its surrounding areas. This work may help in the development of single- or dual-frequency GNSS receivers for civilian navigation services.

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1. INTRODUCTION

The GNSS consist of the GPS, GLONASS, Galileo and Compass systems with global coverage. Currently, the GPS, Glonass and Compass are fully operational and enable autonomous geo-spatial positioning. They are also being gradually modernized. The European Space Agency (ESA) and the European Union (EU) are also working on Galileo, which is the latest civilian-controlled GNSS [1]. Galileo is a more appropriate system for safety-critical applications for civilian users than existing satellite navigation systems. Galileo comprises of 30 MEO (Medium Earth Orbit) satellites constellation. Currently, 22 satellites are operational and are visible from India at different times. Currently, it is not yet fully operational, but the initial services were started in December 2016[1]. Galileo is expected to introduce new modernization elements other than GPS and GLONASS in soon[2]. Because Galileo is still in its early stages with initial services, it is more important to evaluate its performance with existing constellations. Characterizing the Clock and Ephemeris errors of the GNSSs is a key part of validating the assumptions for such integrity evaluation of GNSS Safety-of-Life (SoL) augmentation systems. In the past few years, there haven't been many studies that used both ground-based and space-based GNSS observational data. Some researchers are analysing Galileo's absolute positioning performance in navigation [2, 3]. With ample research demonstrating the benefits of Galileo in multi-GNSS environments in various geographical regions [4-8], there has been a lack of study to demonstrate the performance of Galileo in India, especially with mass-market GNSS receivers. However, very little research on Galileo's performance evaluation over India has been reported [9]. There are also some studies mainly focusing on the accuracy of navigation systems related to multiple GNSS components [10-13]. In this research work, an attempt

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[1] https://www.gsc-europa.eu/system-status/Constellation-Information
[2] https://en.wikipedia.org/wiki/Galileo(satellite_navigation)#cite_note-2

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has been made to enhance position accuracy using integrated ground- and space-based observations. This paper examines the impact of broadcast and precise ephemerides on GPS and Galileo observations over Hyderabad station.

The structure of the paper is as follows: Following the introduction, section 2 provides a brief description of the research approach, focusing on the Lagrange interpolation algorithm used to analyze Galileo and GPS navigation data. Section 3 outlines the results and discussions based on the cases studied. The GPS and Galileo data sets are used, and some issues with precise and broadcast data are identified. The characterization of the observed horizontal accuracy is addressed and discussed in the ENU reference frame, in which the mean and the 50th and 95th percentiles are measured. The paper concludes with final remarks.

2. METHODOLOGY

A highly sensitive multi-GNSS Novatel triple-frequency GPStation-6 receiver with GPS-703-GGG choke ring antenna is used to test the performance of Standalone Galileo and GPS. This was mounted at the Advanced GNSS Research Laboratory (AGRL), Department of Electronics and Communication Engineering, Osmania University, Hyderabad, India. The linear combination positioning solutions of Galileo E1/E5a and GPS L1/L5 observables in receiver independent exchange format (RINEX) files are acquired at 30-second intervals over a 24-hour period. In this paper, the GPS and Galileo satellite positions and satellite clock corrections related to broadcast ephemeris and precise IGS site products are compared. Moreover, the standalone Galileo and GPS' position accuracy capabilities corresponding to both orbital data are also evaluated.

2. 1. Lagrange's Interpolation The GNSS satellites transmit a broadcast ephemeris (BE) composed of Keplerian elements as a navigation message. It enables orbit information to be calculated at any time over a two-hour validity period. Its orbital precision is around 3 m, and its satellite clock accuracy is about 7 ns. The orbit and clock inaccuracies of BE products determine their single-point-positioning (SPP) accuracy. For accurate positioning on the Earth, the precise orbit of GNSS satellites must be known. In contrast to broadcast orbits, precise satellite orbits or precise ephemeris (PE) are more accurate [14]. It is derived directly from the post-mission precise orbital services, specifically IGS [15]. This information contains the precise three-dimensional (3D) positions for all GNSS satellites as well as the satellite clock corrections, which are generally reported in an standard product-3 (SP3) formatted file. Thus, a Keplerian calculation is not necessary to obtain precise satellite orbits [16]. The satellite orbits and the clock corrections provided by IGS are far more accurate than the broadcast orbits, which are 5 cm and 0.1 ns, respectively [17]. Broadcast ephemerides are useful for visibility analysis, observation data quality control, and relative navigation despite their lower accuracy.

The precise IGS orbits are usually available for every 15-minute interval of time. With the interpolation technique, it is possible to obtain precise orbital coordinates with the broadcast sample period [18]. Interpolation is a mathematical technique for deriving new data points from a discrete set of previously known data points. In addition, it facilitates determining the accuracy of broadcast coordinates by comparing them with interpolated precise coordinates [19]. The well-known Lagrange Interpolation has often been used to generate the interpolated PE measurements, in particular for GPS satellites [20, 21]. The Lagrange method is better than Newton's because it can be used with values that are not evenly spaced [22]. The Lagrange formulae (Equations (1) to (4)) are used to determine the value of a mathematical function at any intermediate value of the independent variable.

Let $f_0, f_1, f_2, \ldots, f_n$ be the value of the specific data at time $t_0, t_1, t_2, \ldots, t_n$. An approximation of $f_1$given by $p(t)$, at any time t is given by [23]:

$$p(t) = a_0 f_0 + a_1 f_1 + a_2 f_2 + \cdots + a_n f_n = \sum_{j=1}^{n} a_i f_i \quad (1)$$

where:

$$a_i = \frac{(t-t_0)(t-t_1)\ldots\ldots(t-t_{i-1})(t-t_{i+1})\ldots\ldots(t-t_n)}{(t_i-t_0)(t_i-t_1)\ldots\ldots(t_i-t_{i-1})(t_i-t_{i+1})\ldots\ldots(t-t_n)} \quad (2)$$

Because a_i coefficient is a function of t, it is also known as $L_i(t)$ which stands for Lagrange operator. Now, in Equation (2) we can replace t with $t_0, t_1, t_2, \ldots, t_n$

$$a_i = L_i(t) = \begin{cases} 1, & for\ t = t_i \\ 0, & otherwise \end{cases} \quad (3)$$

Going back to Equation 1 and substituting again t by $t_0, t_1, t_2, \ldots, t_n$, we get:

$$p(t_0) = f_0, p(t_1) = f_1, p(t_2) = f_2, \ldots, p(t_n) = f_n \quad (4)$$

After obtaining the precise interpolated results, the BE and PE measurements are evaluated by comparing satellite ECEF (Earth-Centered-Earth-Fixed) coordinates and clock parameters.

2. 2. User Position Analysis As users are interested primarily in the positioning accuracy of GNSS, the user's position is expressed as latitude (ϕ), longitude (λ), and height/altitude (h) values in a spherical coordinate system (LLA). Generally, a rectangular coordinate system, like ENU is the best to use to quantify position errors in local topo-centric coordinates. The E and N axes are parallel to the orientation of the receiver's latitude and longitude, respectively. On the other hand, the up-axis is perpendicular to both of these axes in the upward direction. To get ENU coordinates, firstly, the conversion between LLA and ECEF coordinates is achieved by using Equation 5. Kuna et al. [24] mentioned formulae are used to get ENU coordinates.

$$X = (\frac{a}{\chi} + h)\cos\phi\cos\lambda$$
$$Y = (\frac{a}{\chi} + h)\cos\phi\sin\lambda \quad (5)$$
$$Z = (\frac{a(1-e^2)}{\chi} + h)\cos\phi\cos\lambda$$

where $\chi = \sqrt{1 - e^2 sin^2\phi}$ here 'a' and 'e' are the semi-major axis and eccentricity of the ellipsoid respectively. Here, the earth's surface is approximated by an ellipsoid with 'a' and the flattening 'f' parameters.

In order to illustrate the systematic error behavior of estimated two-dimensional (2D) user position estimation (which includes east and north dimensions), it will be displayed in a 'scatter plot'. Furthermore, the most popular static 2D position accuracy parameters of GNSS are DRMS (Distance Root Mean Square) and CEP (Circular Error Probability). Here, the radius of a circle is centred at the true position and the position solutions with their associated probability ranges are presented in a scatter plot. Equations in Table 1 represent GNSS static position accuracy measurements, with the standard deviation calculated by computing Equation (6). It is used to figure out the standard deviation of all directional errors after the ENU coordinates have been estimated.

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (6)$$

where x_i is the east component of an estimated i^{th} position sample, $\bar{x}$ be the average measurement of a static position in the east direction. Similar expressions may well be defined for north (y) and up (z) coordinates [25].

3. RESULTS AND DISCUSSION

The article discusses a comparative evaluation based on the satellite and user positions of the standalone GPS and Galileo systems over a low-latitude station. In addition to this, the formal analysis of the orbit accuracy and satellite clock corrections corresponding to BE and PE measurements is presented. The results of data analysis are presented below for individual constellations. The first section examines standalone GPS observations, and the second section examines standalone Galileo observations. At the time of this observation, GPS consisted of 30 satellites, whereas Galileo only had a total of 22 satellites. Instead of examining each satellite, relative to satellite availability at the observation site, GPS pseudorandom noise (PRN) 24 (G24) and Galileo PRN 7 (E7) are considered. It is noticed that the G24 satellite has a less stable block IIF Cesium atomic clock, whereas E7 satellite uses very stable passive hydrogen masers. These two satellite measurements are used to compare orbital accuracy and clock corrections.

TABLE 1. Static positioning horizontal accuracy (2D) measures [20]

Accuracy Parameters	Equation	Probability
CEP	$0.62\,\sigma_x + 0.56\,\sigma_y$	50%
DRMS	$\sqrt{(\sigma_x^2 + \sigma_y^2)}$	65%
2DRMS	$2\sqrt{(\sigma_x^2 + \sigma_y^2)}$	95%

3. 1. Standalone GPS

During GPS week 2177 on September 30, 2021, over the observed station, the G24 has a vicinity period between 00:00:00 and 08:05:12, which corresponds to GPS time between 345600 and 374730 seconds. So, the BE and PE measurements are shown along with the G24 satellite's orbits and clock corrections during the aforementioned time period.

3. 1. 1. Lagrange Interpolation Results

Figure 1 illustrates the similar orbital behavior of the G24 for both precise and interpolated ECEF measurements. In this figure, the y-axis denotes the GPS satellite position data samples, while the x-axis represents the amount of time that the GPS satellite was visible. The SP3 data file's X, Y, and Z coordinates with 5 minutes sample period for the GPS satellite in the ECEF coordinate system are signified as a dotted line (Figure 1(a)). By interpolation, 289 number of initial samples are increased to 3853 samples. Figure 1(b) represents smoothed interpolated path of XYZ coordinates of GPS satellite with increased time samples for every 30 seconds along the X axis. It reveal the behaviour of the interpolation algorithm, but not the accuracy of the coordinates. In three TOWC (Time of Week Count) periods, there were discontinuities between 351000 and 351480 seconds, 357000 and 358080 seconds, and 367800 and 368280 seconds are observed. In UTC (Coordinated Universal Time) (hrs:min:sec), the discontinuities are 01:29:42 (hrs:min:sec) to 01:37:42 (hrs:min:sec), 03:09:42 (hrs:min:sec) to 03:27:42 (hrs:min:sec), and then 06:09:42 (hrs:min:sec) to 06:17:42 (hrs:min:sec). There are several reasons for this kind of discontinuities usually occurs, but primarily due to BE's updating.

Figure 2 (a-c) illustrates the variation in computed broadcast coordinates and interpolated precise ECEF coordinates of the G24 satellite. It is noticed that the X, Y and Z coordinates using BE and PE overlap each other; the differences are minor. Figure 2(d) shows a comparison between both ECEF coordinates related to BE and PE, during the satellite vicinity period. In view of the all-estimated satellite ECEF coordinates, the difference between BE and PE is in the 4 metre range only. On Figure 3(a), the orientation of the G24 satellite is illustrated in relation to its elevation angle. This satellite with zero elevation has been observed at TOWC between 374760 and 432000 seconds, corresponding to UTC times between 05:05:42 (hrs:min:sec) and 19:55:42 (hrs:min:sec). As part of this observation, it was noted that the G24 had orientation between lower (<10°) and higher (>50°) elevations. The G24 satellite clock corrections related to BE are overlaid on those for PE (Figure 3(b)). Also, a similar pattern of discontinuities is seen in Figure 3(b). The clock discontinuities are the difference between the current and prior broadcast ephemeris sets' clock offsets. The BE-PE clock corrections difference is detailed in Figure 3(c), and it is nearly 3 picoseconds or 300 nanoseconds.

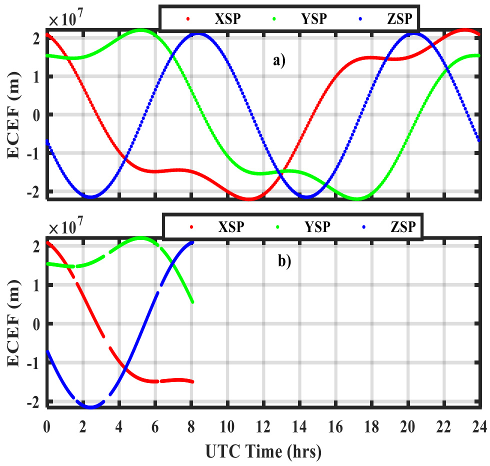

Figure 1. The GPS PRN-24 satellite precise ECEF orbit coordinates derived from a) SP3 file and b) Lagrange interpolated

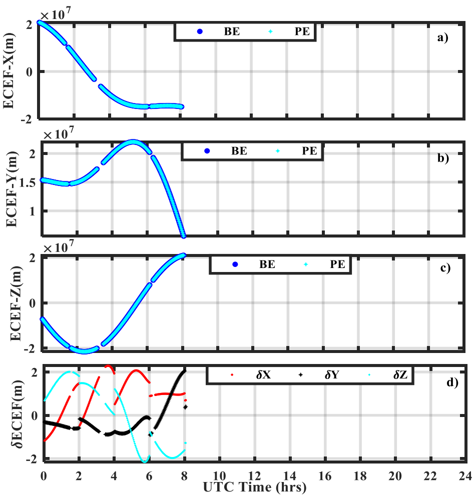

Figure 2. Variation of GPS PRN-24 satellite Broadcast and Precise ECEF a) X-directional b) Y-directional c) Z-directional coordinates and d) Comparison of BE and PE ECEF coordinates during satellite vicinity period

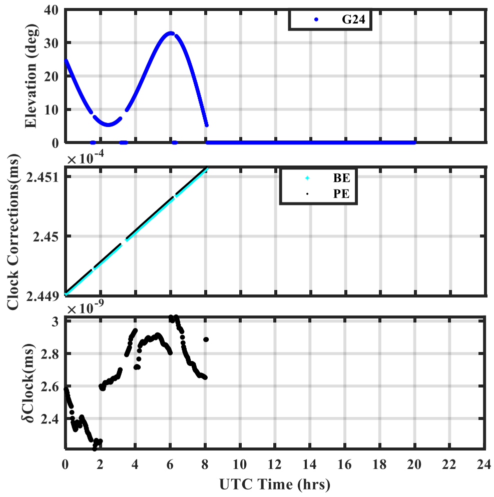

Figure 3. Variation of GPS PRN-24 satellite a) Elevation angle (degrees) b) Comparative variation and c) Deviation between BE and PE Clock corrections corresponding to UTC time

3. 1. 2. User Position Analysis Corresponding to BE and PE

In order to quantify the accuracy of the BE and PE measurements, the user position is computed using the Least Squares (LS) Algorithm, based on both orbital measurements [26]. Figure 4 depicts a scatter plot of the user position latitude and longitudinal variations. It is found that the user positions corresponding to BE and PE are aligned more than 70% of the time, and only a small percentage of user positions are deflected from the reference position. Over a typical day, the receiver tracks a maximum of 12–6 GPS L1, L2, and L5 compatible frequency satellites at the observed location, for a total of 30 satellites. Because the L5 band has only 16 GPS satellites, 9-1 GPS (L1, L5) satellites are visible from the observed location on the observed day, as shown in Figure 5(a). Here, Figure 5 (b-d) shows the variation of estimated ENU coordinates of the user's position based on GPS BE and PE measurements. Table 2 summarized the calculated mean and standard deviation for ENU directional errors related to both BE and PE. In the case of PE-based ENU errors, east errors are much more deviated (mean = 13.97) compared to north (mean = 7.99) and up errors (mean = 4.90). For the GPS, the horizontal accuracy parameters are shown in Table 1, with respective percentile confidence regions. The CEP, DRMS, and 2DRMS for BE and PE measurements were 16.82 m, 20.48 m, 40.96 m, and 13.09 m, 16.10 m, and 32.20 m, respectively, throughout the observed day.

3. 2. Standalone Galileo

During GPS week 2177 on September 30, 2021, over the observed station, the E24 has a vicinity period of between 05:21:00 and

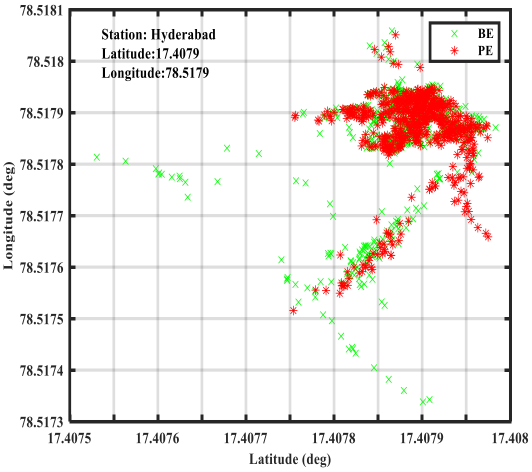

Figure 4. Scatter Plot of Estimated Latitude and Longitudinal variations of standalone GPS on 30 September 2021

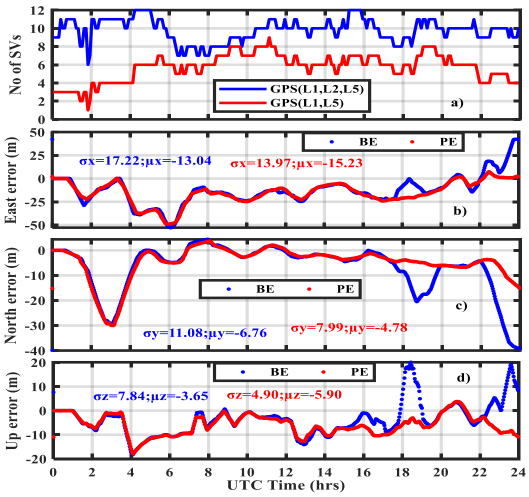

Figure 5. Variations of a) GPS dual and triple frequency Satellite visibility and Comparative variation of BE and PE user position in b) East, c) North and d) Up coordinates (m) with respective standard deviation (m) and mean (m)

16:36:42, which corresponds to GPS time between 364920 and 405420 seconds. So, the orbits of the E24 satellite and the clock corrections for BE and PE measurements are shown during the time period mentioned above.

3. 2. 1. Lagrange Interpolation Results Figure 6 (a-b) shows the E7's orbital behaviour for both precise and interpolated ECEF measurements. In contrast to G24 ECEF coordinates, no discontinuities were detected in E7 satellite coordinates with respect to UTC.

There are several reasons for this, because the GPS system, which use atomic frequency standards like those of block IIR rubidium, IIF cesium, and GPS III rubidium clocks, seems to have a greater proportion of satellites with greater clock noise than Galileo, which employs predominantly highly stable passive hydrogen masers. This drastically reduces Galileo's error rate by decreasing clock prediction error. Secondly, the shortened update period of the orbit information for on-board Galileo satellites provides a significantly higher upload rate of the broadcast navigation data compared to GPS, hence reducing orbit and clock extrapolation errors [8]. This feature of Galileo may be helpful in highly sensitive GNSS applications. Figures 7 (a-c) show how E7 satellite ECEF coordinates change over time. The marginal comparisons of BE and PE satellite coordinates have similar variations and appear to mostly overlap each other. Even the difference is insubstantial, as shown in Figure 7(d).

In view of the all estimated satellite ECEF coordinates, the difference between BE and PE is in the 4 meter range which is quite similar to GPS. On Figure 8a, the orientation of the G24 satellite is illustrated in relation to its elevation angle. The E24 satellite is visible over a minimum 2-hour period with a high elevation angle (>60°). Figure 8b shows the Clock Corrections for BE and PE, which appear to be overlapped on each other. The BE-PE clock corrections difference is detailed in Figure 8c and it ranges approximately to 3ns. It indicates that the clock correction parameters related to BE and PE are quite similar for observed E7 satellite.

3. 2. 2. User Position Analysis Corresponding to BE and PE The scatter plot of user position latitude and longitudinal variation is depicted in Figure 9. There are substantial variations in positioning solutions, and they are widely scattered relative to a fixed receiver reference position. On a typical day, the receiver observes a

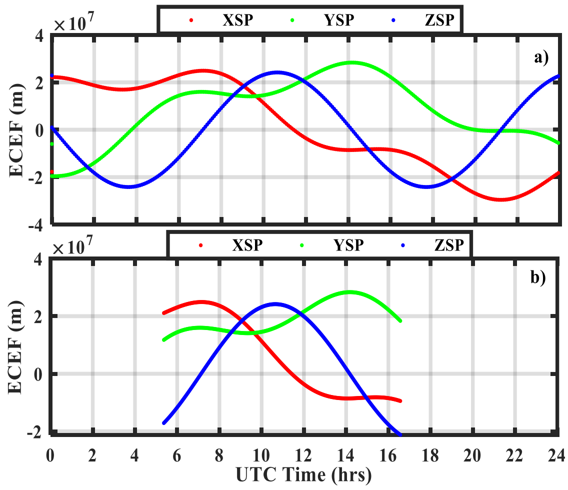

Figure 6. Plot of Galileo PRN-E7 satellite precise ECEF orbit coordinates derived from a) SP3 file and b) Lagrange interpolated

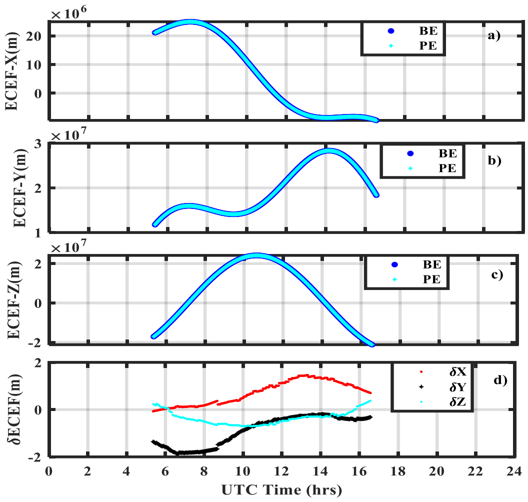

Figure 7. Variation of Galileo PRN-E7 satellite Broadcast and Precise ECEF a) X-directional b) Y-directional c) Z-directional coordinates and d) Comparison of BE and PE ECEF coordinates during satellite vicinity period

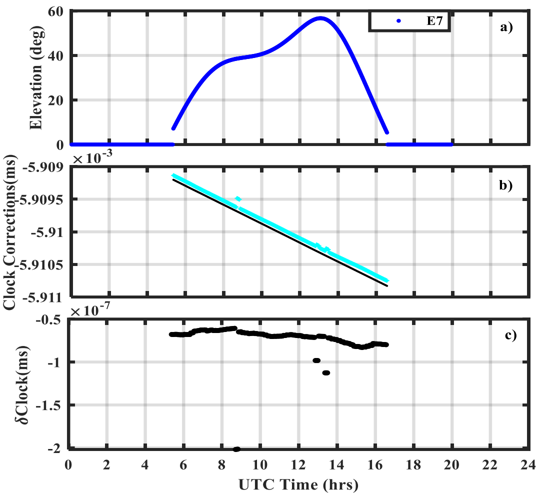

Figure 8. Variation of Galileo PRN-E7 satellite a) Elevation angle (degrees) b) Comparative variation and c) Deviation between BE and PE Clock corrections corresponding to UTC time

maximum of 9 and a minimum of 5 satellites, out of the 22 deployed Galileo satellites, as illustrated in Figure 10 (a). Figure 10 (b-d) depicts the estimated ENU coordinates of user position, mean, and standard deviation for the BE and PE orbits of the Galileo constellation. In the case of PE-related ENU directional errors, Table 2 reveals that the east error (mean = 14.30 m) is significantly more deviated (similar to GPS) than the north and up directional errors (mean = -1.99 m and -5.42 m, respectively). Table 3 contains the standard deviation values for positional errors. For Galileo, the standard deviation of east, north, and up computations employing PE measurements are 69%, 62%, and 77% more precise than with BE measurements, respectively. In contrast, the standard deviations of east, north, and up directional errors for GPS PE measurements are 18%, 27%, and 37% more accurate than BE measures, respectively. Table 4 shows the 2D horizontal position precision characteristics. During the observed day, the CEP, DRMS, and 2DRMS with respective percentile confidence areas for Galileo BE and PE measurements are 12.13 m, 16.22 m, 32.45 m and 3.86 m, 5.01 m, 10.03 m. The Galileo has a more precise horizontal accuracy than GPS, whose 95th percentile value is approximately three times greater at 32.20 m compared to 10.30 m.

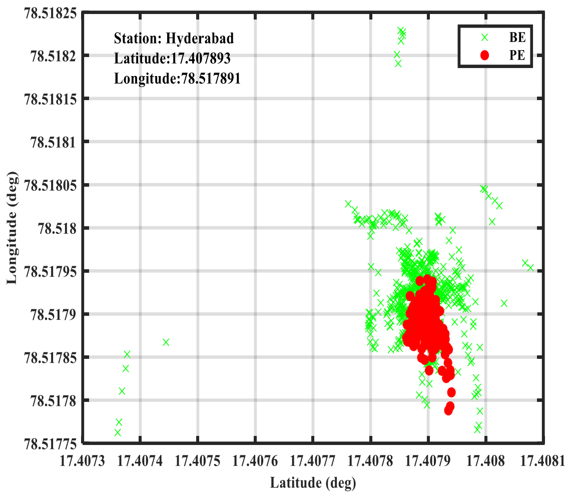

Figure 9. Scatter Plot of Estimated Latitude and Longitudinal variations of standalone Galileo on 30 September 2021

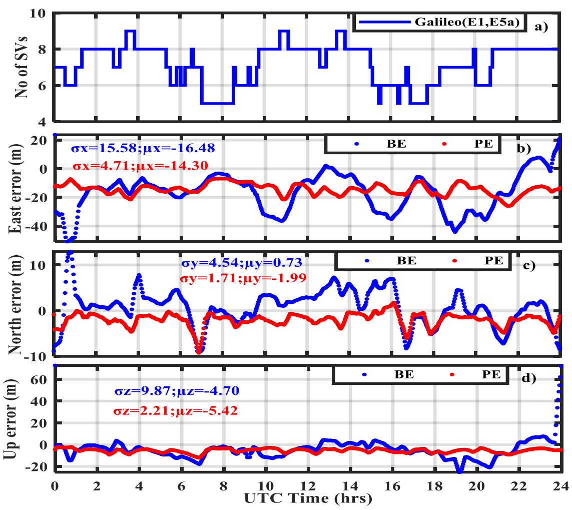

Figure 10. Variations of a) Galileo dual frequency Satellite visibility and Comparative variation of BE and PE user position in b) East, c) North and d) Up coordinates (m) with respective standard deviation (m) and mean (m)

TABLE 2. Mean of the East, North and Up directional errors (m) for Standalone GPS and Galileo on 30 September 2021 (DOY-273)

Constellation	Measurements	Mean (m)		
		East	North	Up
Standalone GPS	BE	-13.04	-6.76	-3.65
	PE	-15.23	-4.78	-5.90
Standalone Galileo	BE	-16.48	0.73	-4.70
	PE	-14.30	-1.99	-5.42

TABLE 3. Standard deviations in the ENU coordinate system for Standalone GPS and Galileo on 30 September 2021 (DOY-273)

Constellation	Measurements	Standard Deviation(m)		
		East	North	Up
Standalone GPS	BE	17.22	11.08	7.84
	PE	13.97	7.99	4.90
Standalone Galileo	BE	15.58	4.54	9.87
	PE	4.71	1.71	2.21

TABLE 4. The Horizontal precision estimation parameters as CEP, DRMS, and 2DRMS values for Standalone GPS and Galileo on 30 September 2021 (DOY-273)

Constellation	Measurements	CEP (m)	DRMS (m)	2DRMS (m)
Standalone GPS	BE	16.82	20.48	40.96
	PE	13.09	16.10	32.20
Standalone Galileo	BE	12.13	16.22	32.45
	PE	3.86	5.01	10.03

4. CONCLUSIONS

The performance of SPP is evaluated in order to assess the GPS and Galileo satellites' precise and broadcast measurements as well as clock offsets over a low latitude station. During the observation period, the E7 satellite has a better clock offset of 3 ns than the G24 satellite (300 ns) with BE and PE measurements. It is noticed that Galileo outperforms GPS with more L1-L5 satellite visibility and a high update rate of navigation messages over the observation period. The numerical results show that the GPS north, east, and vertical components typically improve about 63%, 15%, and 13%, while Galileo improves by 41%, 14%, and 38% corresponding to PE measurements. The PE measures improve CEP and 2DRMS values by 68% and 69% for Galileo and 22% and 21% for GPS, respectively. During the observations, it was observed that the Galileo offers better accuracy than the GPS with PE measurements and low clock offset error. This kind of analysis is useful for future research with regional and global constellations in low-latitude areas.

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Persian Abstract

چکیده

سیستم ماهواره ای ناوبری جهانی ((GNSSدر حال تبدیل شدن به یک فناوری موقعیت یابی حیاتی در سرویس های مختلف است. کیفیت ephemeris یکی از عواملی است که مستقیماً بر دقت موقعیت کاربر تأثیر می گذارد. برخی از برنامه ها، مانند تحقیقات در مورد پویایی پوسته زمین، به داده های زودگذر دقیق تری نسبت به گذراهای پخش شده نیاز دارند. چندین مؤسسه، مانند سرویس بین المللی GNSS (IGS)، خدمات مداری دقیقی را برای فعال کردن این برنامه ها توسعه داده اند. متأسفانه، نرخ داده برای چنین مدارهای دقیقی اغلب به ۱۵ دقیقه محدود می شود. در این مقاله، به منظور تولید ابطال دقیق با دوره نمونه‌برداری پخش، از روش درون یابی معروف لاگرانژ استفاده شده است. علاوه بر این، یک تجزیه و تحلیل موقعیت GPS و گالیله مقایسه ای مربوط به پخش و قطعی دقیق در یک روز معمولی در سپتامبر ۲۰۲۱ ارائه شده است. برای به دست آوردن بینش در مورد تجزیه و تحلیل موقعیت یابی مقایسه ای بر روی ایستگاه حیدرآباد، خطاهای جهت) ENUشرق-شمال-بالا)، دید ماهواره و پارامترهای دقت افقی در نظر گرفته شده است. بر اساس تجزیه و تحلیل عددی، گالیله مستقل دارای قابلیت های مشابه با GPS است و می توان از آن در Multi-GNSS در هند و مناطق اطراف آن استفاده کرد. این کار ممکن است به توسعه گیرنده‌های GNSS تک فرکانس یا دو فرکانس برای خدمات ناوبری غیرنظامی کمک کند.