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Evaluation of Smartphone-Based GNSS Positioning Using Ionosphere Free-Precise Point Positioning in Static Mode

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Abstract

Global Navigation Satellite System (GNSS) positioning with smartphones has increased attention due to its accessibility and potential for high-precision applications. In this study, the accuracy of the multi-constellation multi-frequency Xiaomi 11T module for static applications is investigated. Two-hour static GPS and Galileo measurements are acquired using Xiaomi 11T centered on a reference point at the Arab Academy for Science, Technology, and Maritime Transport in Aswan, Egypt, over a period of three separate days; subsequently, the measurements are processed using the Ionosphere Free-Precise Point Positioning (IF-PPP) processing model. Three processing scenarios are applied including GPS-only, Galileo-only, and combined GPS/Galileo. To account for satellite and clock errors, the final Center for Orbit Determination in Europe (CODE) products are utilized. The results indicate that decimeter- and submeter-level accuracies can be fulfilled in horizontal and vertical directions, respectively; additionally, the combined constellation positioning accuracy are superior to those obtained from single constellation solutions, which is about 50-centimeter and 80-centimeter position accuracies in horizontal and vertical directions, respectively. Moreover, it is found that GPS-only solution is slightly better than Galileo-only solution, while Galileo-only solutions demonstrate slightly better performance in the vertical directions.

Keywords: Xiaomi 11T; Ionosphere-Free PPP; GPS; Galileo; CODE.

1. Introduction

Recently, low-cost Precise Point Positioning (PPP) technique has seen significant advancements because its advantage in achieving centimeter-level positioning accuracy using single GNSS receiver [1]. However, PPP technique is limited by slow convergence, which results from a number of factors such as ambiguity resolution, noisy measurements, and slow changes in satellite geometry [2]. Precise clocks and satellite orbits are both necessary to attain high PPP positioning accuracy. For this purpose, the International Global Navigation Satellite System (GNSS) Service (IGS) offers those products in various forms namely real-time, ultra-rapid, rapid, and final [3], which are publicly available from various analysis centers, for example, the Center for Orbit Determination in Europe (CODE). Eliminating ionospheric effects is the major challenge for PPP processing model particularly for low-cost GNSS devices because ionosphere is a dispersive medium, meaning that the value of the delay is frequency-dependent [4]; therefore, the Ionospheric-Free (IF) combination of dual-frequency GNSS data, including carrier-phase and pseudo-range measurements, can effectively mitigate 99% of its effect which known as the 1st order ionospheric effects [5], [6].

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Currently, smart devices (i.e., smartphones, smartwatches, tablets, etc.) are the dominant GNSS devices as it provides users not only with positioning capabilities but also with telecommunications, entertainment, and various other functionalities. Prior to 2016, GNSS raw data was not accessible through smartphone GNSS chipsets; as a result, enhancing positioning accuracy was not feasible without the use of external hardware or software [7]. With the accessibility of multi-frequency, multi-constellation GNSS smartphone, it becomes possible to improve smartphone GNSS positioning accuracy using a variety of positioning techniques and algorithms [8], [9]. The Xiaomi module, Mi8, achieved centimeter- and meter- level accuracies in static and kinematic PPP modes [10], also it achieved 6.13 m, 4.10 m and 2.23 m accuracies in leaf-on season, leaf-of season and open area, respectively using forest trajectory [11]. In addition, [12] achieved centimeter-level position accuracies in static mode using Google Pixel 5 model using PPP approach. Although smartphones are considered similar to geodetic receivers in tracking multiple GNSS constellations, their carrier-to-noise ratios (*C/N0*) are generally lower, leading to issues such as data loss or missing data [13].

In our paper, we investigate the performance of Xiaomi 11T smartphone for GNSS positioning using IF-PPP approach in static mode. Xiaomi 11T has been released since 2021 as a new dual frequency multi constellation module [14]. The following section introduces the traditional IF-PPP mathematical model, and Section 3 introduces the GNSS data processing including data acquiring, data quality and data processing parameters; additionally, Section 4 presents the processing outputs along with their analysis. Finally, the conclusion is provided in Section 5.

2. Ionosphere–Free PPP mathematical model

The GPS/Galileo observation equations are given below [15]:

$$P_i^J = \rho^J + cdt_r^J - cdt^{sJ} + T^J + I_i^J + {b_{Pi}^r}^J - {b_{Pi}^s}^J + \varepsilon_{pi}^J \quad (1)$$

$$\Phi_i^J = \rho^J + cdt_r^J - cdt^{sJ} + T^J - I_i^J + {b_{\Phi i}^r}^J - {b_{\Phi i}^s}^J + \lambda_i N_i^J \varepsilon_{\Phi i}^J \quad (2)$$

where the superscript (^{J}) refer to the GNSS system either GPS or Galileo, P_i and Φ_i are pseudo-range and carrier measurement on L_i frequency respectively; dt_r and dt^s are receiver clock errors and satellite clock error respectively; b_{Pi}^r and b_{Pi}^s are the code biases of receiver and satellites respectively; $b_{\Phi i}^r$ and $b_{\Phi i}^s$ are the phase biases of receiver and satellites respectively; T is tropospheric delay; I_i is ionospheric delay on L_i frequency; λ_i is wavelength on L_i frequency; N_i is carrier-phase ambiguity parameter on L_i frequency; $\varepsilon_{(p_i,\Phi_i)}$ are multipath and measurement noise for code and carrier measurements in meter.

Taking advantages of 11T dual frequencies (GPS L_1, GPS L_5, Galileo E_1, Galileo E_{5a}), the GPS/ Galileo PPP-IF model can be written as follow:

$$P_{IF}^G = \rho^G + (c.dt_r^G + {b_{P_{IF}}^r}^G) - (c.dt^{sG} + {b_{P_{IF}}^s}^G) + T^G + \varepsilon_{p_{IF}}^G \quad (3)$$

$$\Phi_{IF}^{G} = \rho^{G} + (c.dt_{r}^{G} + {b_{p_{IF}}^{r}}^{G}) - (c.dt^{sG} + {b_{P_{IF}}^{s}}^{G}) + T^{G} + \widetilde{N_{IF}}^{G} + \varepsilon_{\Phi_{IF}}^{G} \quad (4)$$

$$P_{IF}^{E} = \rho^{E} + \left(c.dt_{r}^{G} + {b_{P_{IF}}^{r}}^{E}\right) - \left(c.dt^{sE} + {b_{P_{IF}}^{s}}^{E}\right) + T^{E} + ISB + \varepsilon_{p_{IF}}^{E} \quad (5)$$

$$\Phi_{IF}^{E} = \rho^{E} + \left(c.dt_{r}^{G} + {b_{p_{IF}}^{r}}^{E}\right) - \left(c.dt^{sE} + {b_{P_{IF}}^{s}}^{E}\right) + T^{E} + \widetilde{N_{IF}}^{E} + ISB + \varepsilon_{\Phi_{\mathrm{IF}}}^{E} \quad (6)$$

where the superscripts (^{G}) and (^{E}) refer to GPS and Galileo systems respectively, $b_{p_{IF}}^{r}$ and $b_{p_{IF}}^{s}$ are the receiver and satellite ionosphere-free differential code biases, respectively; $\widetilde{N_{IF}}$ represent real-value ambiguity including both code and carrier phase biases and *ISB* is the inter systems biases between GPS and Galileo. The troposphere dry (T_H) component accounted by using Saastamoinen model, while the wet component (T_W) will be estimated as unknown parameters. The final CODE products account for satellites orbit and clock biases as well as satellites code phase hardware delays. The Vector of Unknown Parameters for PPP-IF Model ($\overrightarrow{X_{PPP-IF}}$):

$$\overrightarrow{X_{PPP-IF}} = [\,X, \quad Y\,, \quad Z, \quad cdt_{r}^{G}, \quad ISB, \quad T_{W}, \quad \widetilde{N_{IF}^{G}}, \quad \ldots\ \widetilde{N_{IF}^{E}}] \quad (7)$$

where (X, Y, Z) are the smartphone coordinates in Earth Center Earth Fixed (ECEF) frame.

3. Smartphone GNSS Data Processing

Static GNSS raw datasets are acquired from Xiaomi 11T module on Days of Year (DOY) 70, 71, and 72 over Arab Academy for Science, Technology and Maritime Transport, Aswan, Egypt reference point (ASMT-9) as illustrated in (Figure 1). The GNSS data is obtained from a smartphone using the GEO++RINEX mobile application with 30-second interval [16]. It should be said that the Xiaomi 11T smartphone supports the second frequencies (i.e., GPS L_5 and Galileo E_{5a}) in the *Q* channel (pilot or data-less) as illustrated in (Table 1) [17]; additionally, the GPS L_5 signal is transmitted only by Block II and Block III/IIIF satellites, which are satellites G01, G03, G04, G06, G08, G09, G10, G11, G14, G18, G23, G24, G25, G26, G27, G30, and G32 [18]. Therefore, a proper pre-mission planning is crucial for ensuring that a sufficient number of GPS L_5 satellites has been tracked, which is essential for obtaining an accurate IF-PPP solution. In our research, pre-mission planning is carried out using the Trimble GNSS Planning free online service [19].

Figure 1. Xiaomi 11T centering over ASMT-9 point.

Table 1. Characteristics of 11T module datasets.

Receiver	GPS	Galileo
Xiaomi 11T	C1C L1C D1C S1C C5Q L5Q D5Q S5Q	C1C L1C D1C S1C C5Q L5Q D5Q S5Q

The open-source raPPPid GNSS software package is utilized to process the collected datasets in IF-PPP mode; this software facilitates both analysis of raw data and processing of single-, dual- and triple-frequency GNSS observations through various PPP approaches. Furthermore, it is capable of handling observation data from low-cost, low-quality receivers, such as smartphones; moreover, it has been developed in the MATLAB environment offering a user-friendly Graphical User Interface (GUI) that enhances the ease of data processing and analysis for users [20], [21].

(Figure 2) depicts the number of the tracked GPS and Galileo satellites processed, and it is shown that, in general, Galileo observations exceed that of GPS observations with the exception on DOY 72. This is attributed to the fact that the number of L_5 GPS satellites are few compared with the tracked Galileo satellites; furthermore, the number of tracked satellites increases when GPS and Galileo observations are combined.

To evaluate the quality of the datasets, the carrier-to-noise density (*C/N0*) ratio is examined for all processed signals, which is quantifies the relative strength of the received carrier signal to the noise power encountered during signal propagation; thereby, it provides an indication of the measurement's noise level [22]. (Figures 3-5) show C/N0 values, and it can be noticed that the first frequencies (L_1, E_1) were generally superior to the second frequencies (L_5, E_{5a}) across all satellites, with the exception of satellites E05 and E19; moreover, the *C/N0* values of GPS satellites are observed to be superior to those of Galileo satellites. As a result, the *C/N0*-based model weighting scheme is employed to stochastically process our datasets [23]. (Table 2) summarize the raPPPid GNSS software parameters for IF-PPP solution.

4. Results and Analysis

(Figures 6-7) show the horizontal (2D) and vertical (V) errors over the three days, respectively; the 2D positioning error takes the following formula:

$$2D_{Errors} = \sqrt{Easting_{Errors}^2 + Northing_{Errors}^2} \quad (7)$$

It can be seen that the GPS and combined GPS/Galileo processing models demonstrate convergence to less than 1 meter and 50 centimeters for the vertical and horizontal components, respectively, after 30 minutes, while the Galileo processing model converge to 1 meter and less than 1 meter for the vertical and horizontal components, respectively, after 30 minutes. Although the number of GPS L_5 satellites is fewer than the Galileo E_{5a} satellites, GPS solutions exhibit slightly better performance compared to Galileo solutions; on the other hand, the Galileo solution show superior performance in terms of vertical accuracy.

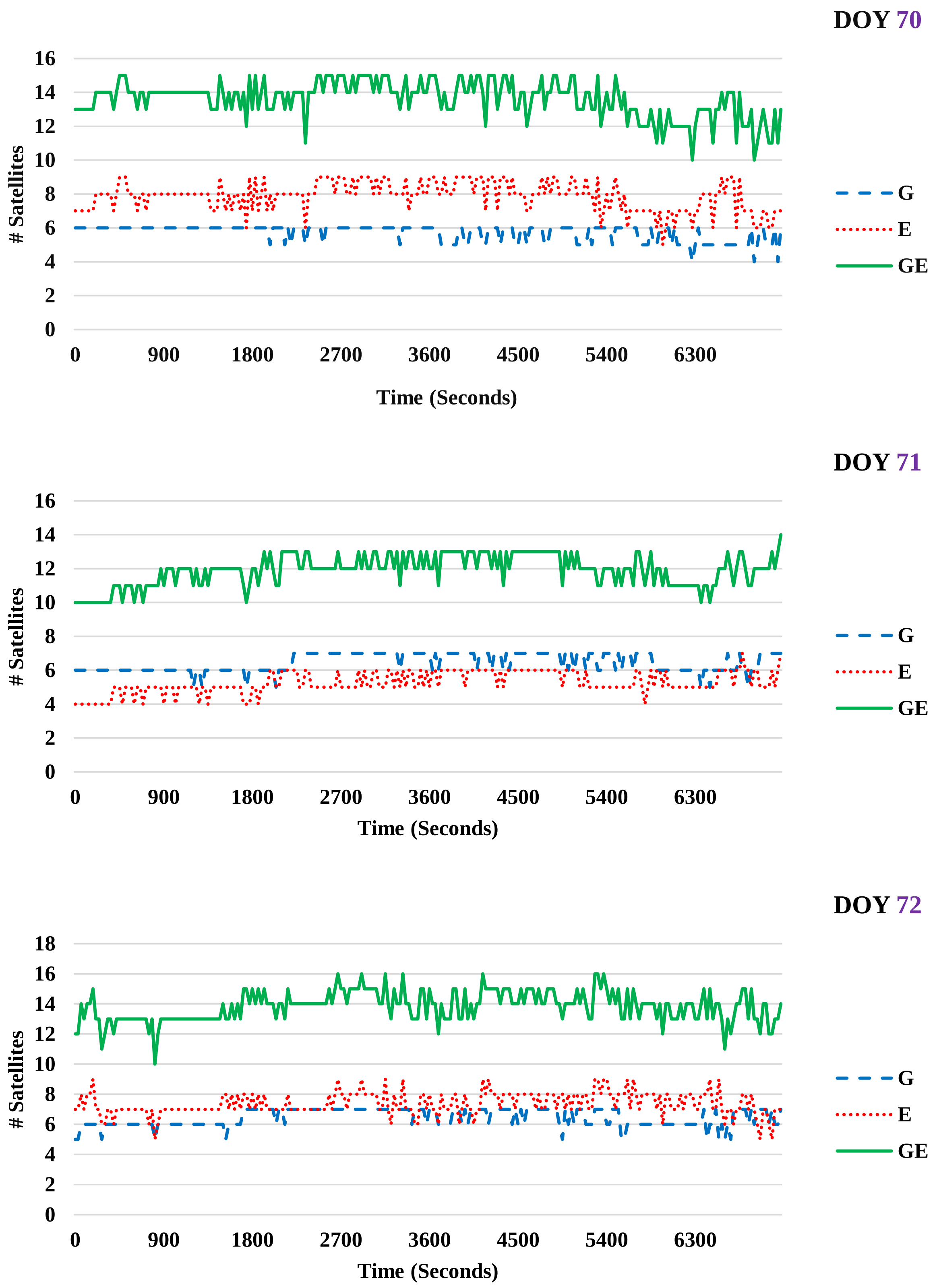


Figure 2. The number of processed satellites during the dataset for DOY 70, 71, and 72.

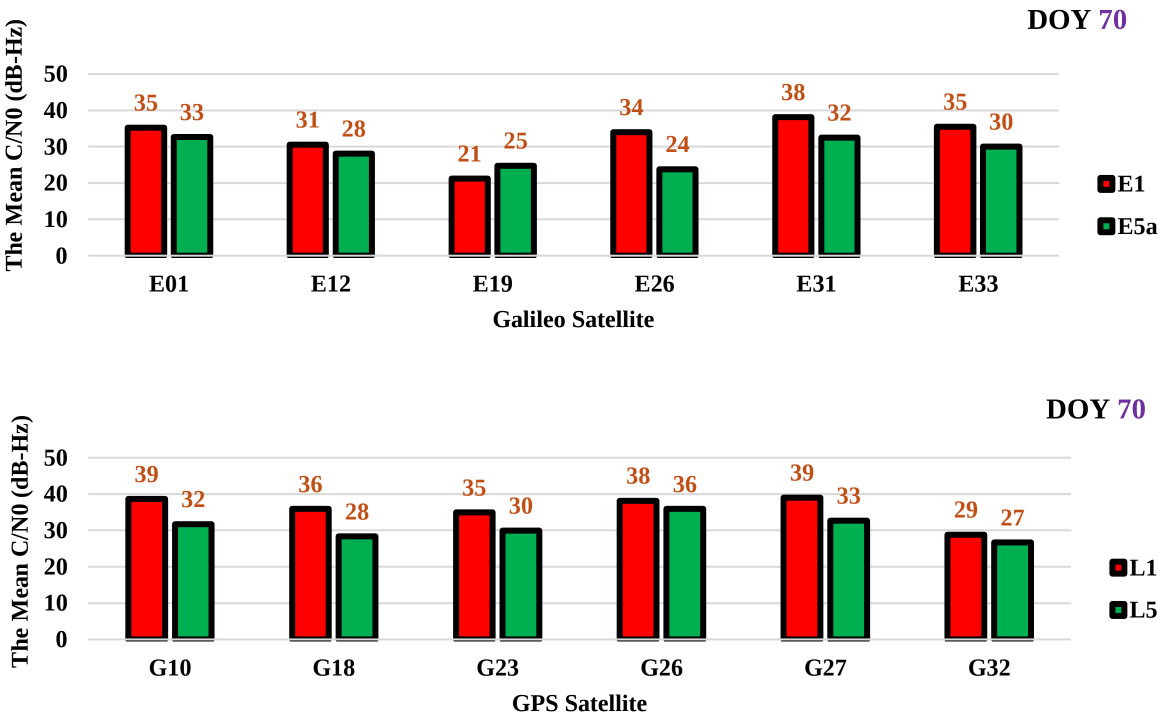


Figure 3. The mean *C/N0* for Galileo and GPS satellites on DOY 70.

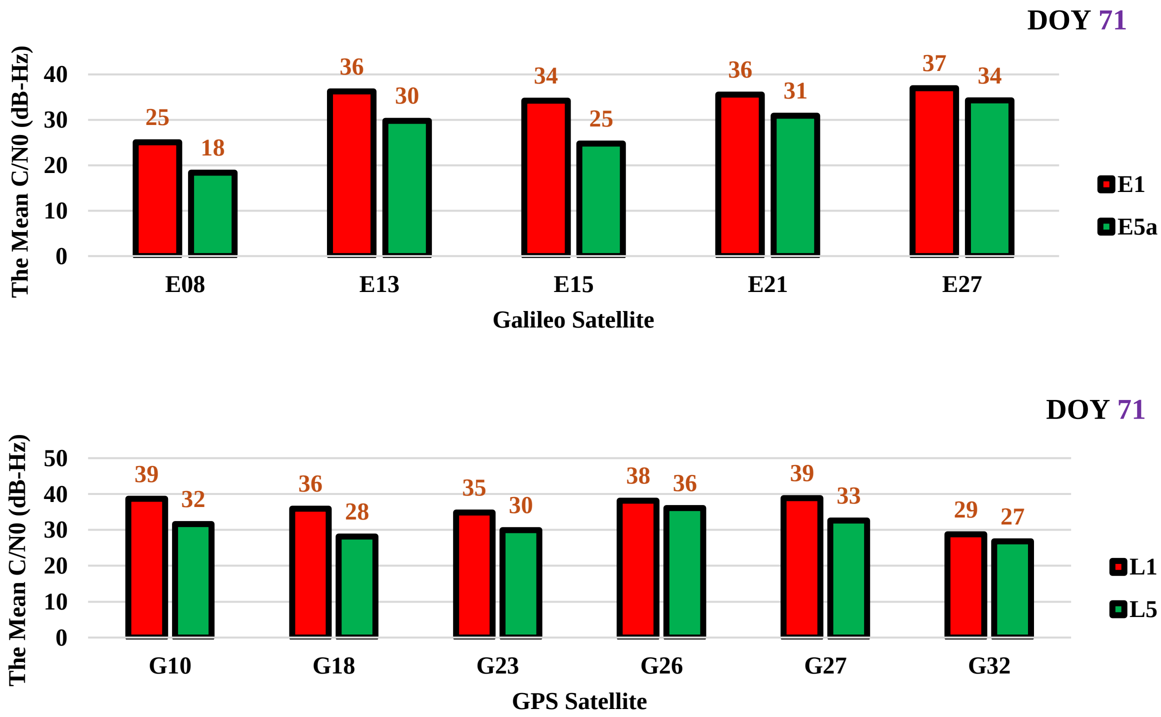


Figure 4. The mean *C/N0* for Galileo and GPS satellites on DOY 71.

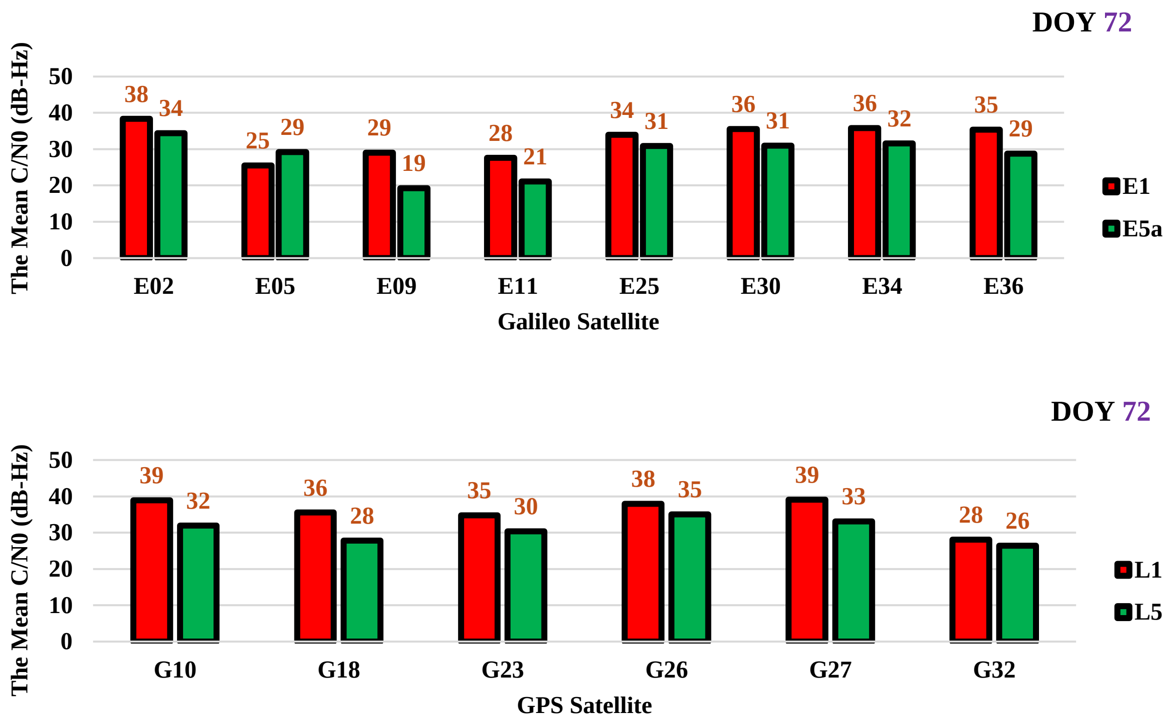
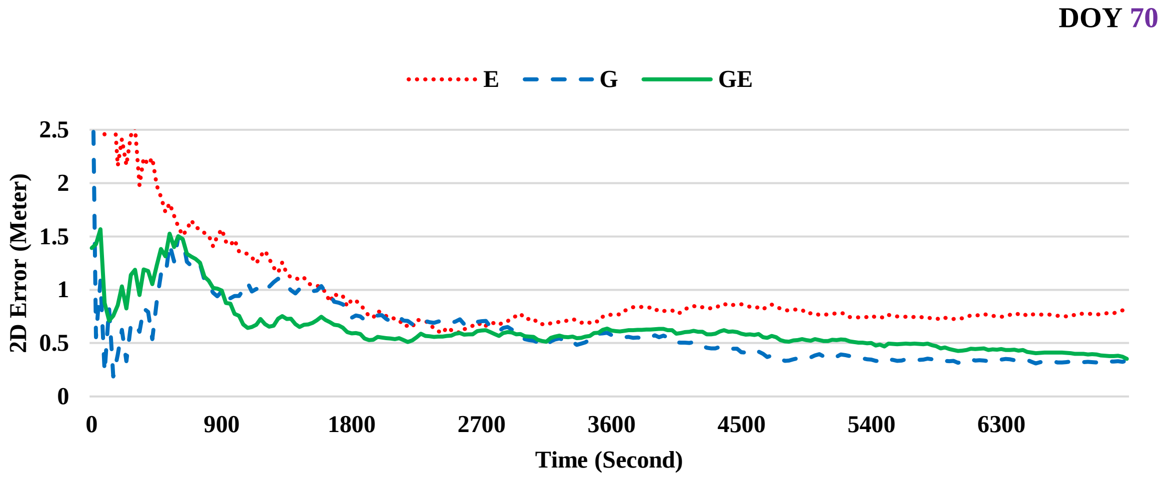


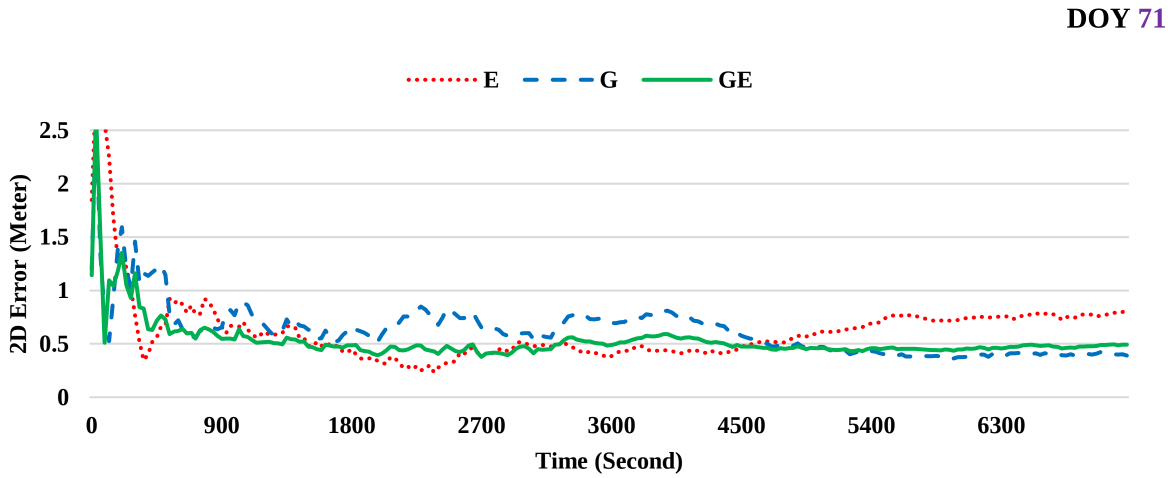
Figure 5. The mean *C/N0* for Galileo and GPS satellites on DOY 72.

Table 2. raPPPid GNSS software parameters for IF-PPP.

Satellite Orbit	Final [CODE]
Tropospheric model	Saastamoinen
Cut of angel	5°
Observation Type	Code Carrier [P+C] Adjust Code to Phase [ON]
Ionospheric Correction	Ionosphere Free Model
Combination	GPS [L_1/L_5] Galileo [E_1/E_{5a}]
Ambiguity resolution	Float
Parameter estimation	Kalman Filter Iterative
Stochastic Model	SNR

Table (3) shows the Root Mean Square Error (RMSE) values, which are computed to further investigate the accuracy of the IF-PPP scenario using Xiaomi 11T module. The results demonstrate that the combined GPS/Galileo solution outperforms the other solutions achieving an RMSE of 0.48 meters for the 2D component and 0.42 meters for the vertical (V) component on DOY 71; on other hand, the GPS solution shows RMSE values of 0.58 meters and 0.73 meters for the 2D and vertical components, respectively, on DOY 71 as well as the Galileo solution shows RMSE values of 0.58 meters for the 2D component and 0.33 meters for the vertical component on DOY 71. In general, it is indicated that by using final CODE products, positioning accuracies at sub-meter level for the vertical component and under 50-centimeter level for the horizontal component can be attained.





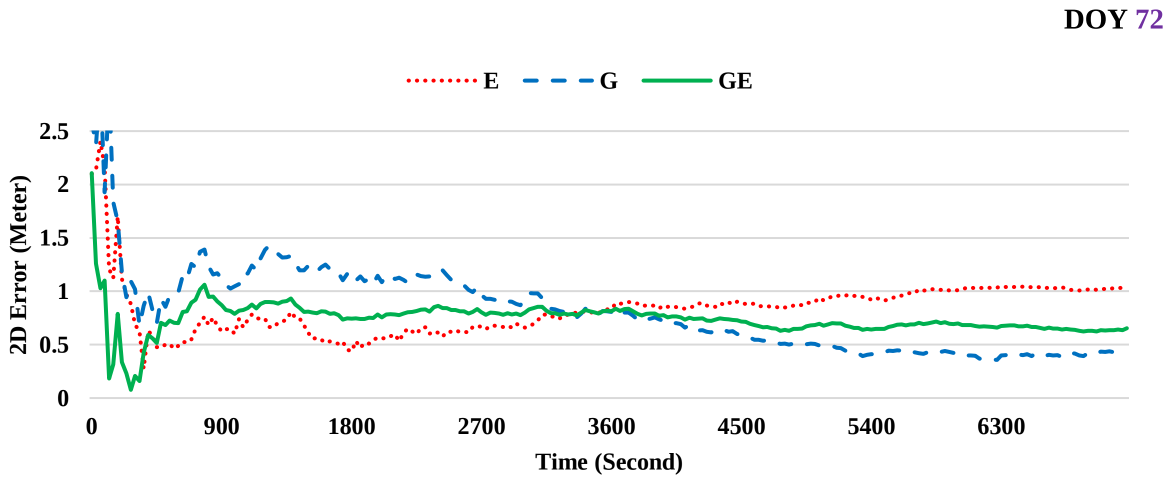


Figure 6. The horizontal (2D) errors on DOY 70, 71 and 72.

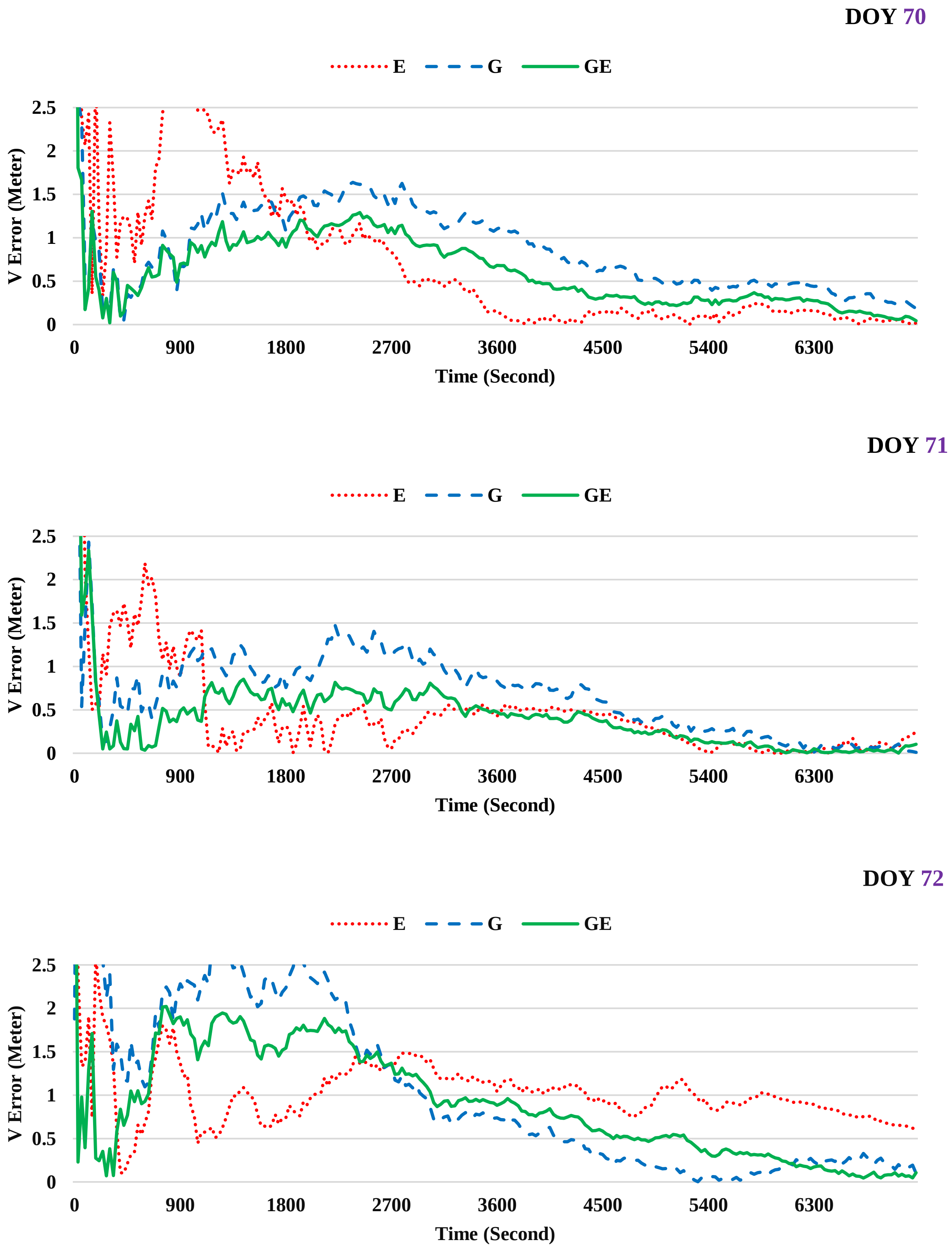


Figure 7. The vertical (V) errors on DOY 70, 71 and 72.

Table 3. The RMSE values (in meter) for PPP-IF solution.

Type	Products	G		E		GE		DOY
		2D	V	2D	V	2D	V	
Final	CODE	0.50	0.93	0.76	0.50	0.53	0.65	70
Final	CODE	0.58	0.73	0.58	0.33	0.48	0.42	71
Final	CODE	0.72	0.95	0.87	1.04	0.73	0.89	72

5. Conclusion

In our paper, the performance of Xiaomi 11T smartphone for static applications has been examined. For this purpose, static GPS/Galileo measurements have been collected; then, data quality assessment has been achieved. The findings revealed that the first frequencies (GPS L_1, Galileo E_1) showed greater stability and superior performance compared to the second frequencies (GPS L_5, Galileo E_{5a}); additionally, the GPS signals tracked by the Xiaomi 11T demonstrated higher *C/N0* values in comparison with the Galileo signals. The IF-PPP processing model has been used with final CODE satellite orbit and clock products. It has been found that sub-meter and sub-50-centimeter positioning accuracy levels have been attained for both horizontal and vertical components, respectively.

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