Performance Comparison of Global Navigational Satellite Systems

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Summary

The Global Navigational Satellite Systems (GNSS) are widely used to determine the position and velocity of objects on the earth. In this paper, we provide the performance comparison of two widely used GNSS i.e., Global Positioning System (GPS), Global Orbiting Navigational Satellite System (GLONASS), and hybrid GPS+GLONASS. The position data in RINEX format is collected by placing the GNSS receiver in an open urban area. For our experiments, we have collected the data in the city of Islamabad (Capital city of Pakistan); that has average human population density and is surrounded by hills. The performance comparison is conducted in terms of various evaluation measures such as receiver positioning accuracy, Signal to Noise Ratio (SNR), Dilution of Precision (DOP), and satellite visibility. The integration of GPS with GLONASS results in further improvement in positioning accuracy of GLONASS but less than that of GPS alone. The overall results show that GPS performs well in comparison to both GLONASS and hybrid GPS+GLONASS.

Key words:
Global navigational satellite system (GNSS); Global positioning system (GPS); Global orbiting navigational satellite system (GLONASS); Dilution of precision (DOP); Satellite visibility;

1. Introduction

Global Navigation Satellite System (GNSS) is broadly used to provide navigation facilities and become an integral part in applications, which are being used for mobility. The GNSS provides position and velocity information of objects. Nowadays, the GNSS has revolutionized the world and commonly used in both civil and military related services. Currently, GNSS has a vital role in every aspect of life e.g., vehicle tracking [1], weather prediction [2], route planning [3], aviation navigation [4], mobile communication [5], land surveying [6], agriculture [7], and various other applications [1]. Different countries have established their particular navigational systems for global and regional coverages. Among these, most commonly used are Global Positioning System (GPS) [8], Global Orbiting Navigational Satellite System (GLONASS) [8], Galileo [9], Compass (BeiDou) [10], India Regional Navigation Satellite System (IRNSS) [11], and Quasi-Zenith Satellite System (QZSS) [12].

The microwave radio signal comprising of two codes, two carriers and a navigation message, is constantly transmitted by the navigation satellite. When the GNSS receiver is powered on, it starts picking up the signal through the antenna and processed using the GNSS software. The purpose of this processing is to identify the satellites, hence to find the frequency and the code phase. The distance from the GNSS satellites and the receiver coordinates can be calculated from the navigation message and digital codes that contain ephemeris data. The total number of satellites in the GNSS should be large enough to ensure that at least four satellites remain in view every time.

The three major components of GNSS are the space segment, the control segment, and the user segment. The space segment includes GNSS satellites orbiting at about 20,000km distance from the earth. The main tasks of space segment are receiving, processing, and storing of information transmitted from the ground station. A space vehicle number and pseudorandom noise are utilized to identify the satellites. The task of control segment is to track, monitor, upload data, provide service protection, and to maintain the clock and encryption of data. The control stations are used to command, control, and track satellites. The user segment is used for processing the received information from GNSS satellite and to determine the position and velocity of receiver. Every GNSS provides different specifications in terms of positioning, tracking, and monitoring. The performance and accuracy of GNSS is evaluated using set of parameters. The accuracy of GNSS is usually depending on the quality of the received data. In the literature, the performance evaluation of different GNSS is being conducted using Dilution of Precision (DOP), accuracy measures, Signal to Noise Ratio (SNR), and satellite visibility [13-15].

Initially, Langley in [16] used DOP to observe the impact on GPS positional accuracy. It was concluded that DOP has important role in determining GPS position accuracy and using new signals and upgradation of receiver’s design may result in reduction of DOP values, hence

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improvement in performance. Yahya et al. in [17] checked the satellite visibility and geometry of GPS satellites at different regions. The results showed that a great number of satellites were visible at equatorial regions compared to the high latitude or mid latitude regions. The smaller GDOP was achieved at the equatorial region. Chen et al. in [18] checked the performance of GPS, Compass, and BeiDou based on satellite visibility and DOP. The results showed that the performance of GNSS in Asia region is better than other countries. Misra et al. in [19] compared the performance of GPS, GLONASS, and a combination of both. The results showed that the performance of GPS can be increased by adding more signals to the space segment.

Dogan et al. in [20] checked the seasonal behavior of a GPS using Root Mean Square (RMS) accuracy measure. The results showed that RMS values of horizontal components were higher than vertical components. It was also investigated that GPS position accuracy in the summer season was better than the winter season. Hlubek et al. in [21] checked the ionosphere effects on the signals of GLONASS, GPS, and Galileo. The results showed that after sunset, scintillation strength is greater for Galileo than other navigation system. Rabbou et al. in [22] investigated kinematic model of GPS, GLONASS, and GPS+GLONASS. The results showed that the positioning accuracy of GLONASS is lower than that of GPS. Li et al. in [23] checked the positioning of Galileo, GPS, GLONASS, and BeiDou. The results showed that the coverage of Ionospheric Piecing Points (IPP) distributions of GPS and GLONASS is worldwide, and has particular coverage of BeiDuo and Galileo systems. Rajasekahar et al. in [24] checked the positioning accuracy of GPS, IRNSS, and GPS+IRNSS using GDOP. The results showed that the GDOP is directly related to positioning accuracy. Cai et al. in [25] performed the analysis of GPS, BeiDou, GLONASS, and Galileo by taking into account multipath effects and noise. The results showed that the RMS value of GLONASS is highest for phase noise and multipath. Eissfeller et al. in [13] checked the performance of GLONASS, GPS, and Galileo. The study concluded that the Galileo is not available but planned to introduce 30 new satellites and has ability of integrity, authenticity, and geometry of satellites is same like GPS. Satirapod et al. in [15] used SNR and satellite elevation angle as quality indicators for GPS position data. The results showed that these two indicators are not enough to check the performance, and more quality indicators are needed for better performance evaluation. Liu et al. in [26] demonstrated that the combined use of GPS and GLONASS resulted in an increase in the positioning accuracy.

Based on the literature study, we observe that different authors use one or two measures for GNSS performance evaluation. In this work, we have used all the existing measures i.e., accuracy, DOP, SNR, and visibility to compare the performance of GPS, GLONASS, and integration of both i.e., hybrid GPS+GLONASS. The main objective of the research work is to conduct performance comparison tests based on the receiver positioning accuracy of different navigation constellations. The main contributions in terms of performance evaluation are:

(i) To investigate different accuracy measures to check the positional accuracy.

(ii) To analyze the satellite visibility to check the availability of number of navigation satellites.

(iii) To investigate the SNR to check the best positioning and accuracy.

(iv) To analyze the DOP to check the satellite geometry by which we estimate best positioning accuracy

The rest of the paper is organized as follows. In Section 2, we provide the detailed descriptions of different GNSS. Section 3 discusses performance evaluation criterions used for GNSS. In Section 4, we discuss the methodology and experimental results while Section 5 will conclude the paper.

2. Types of Global Navigation Satellite Systems

With the passage of time, different countries have developed their own GNSS like GPS (United States of America), GLONASS (Russia), Galileo (European Union), BeiDou (China), Compass (China), IRNSS (India), and QZSS (Japan). Here we discuss in detail each GNSS type

2.1 Global Positioning System (GPS)

The GPS is the first GNSS system started by the US department of defense for military purposes only. In 1977, the first GPS satellite was launched and it became operational in 1995. The GPS has three segments i.e., space segment, control segment, and user segment. The GPS consists of 31 satellites orbiting around the earth at an altitude approximately 12,500 miles from the earth, arranged in 6 planes (four in each), and moving with the velocity of almost 7,000 miles per hour (completes about two revolutions around the earth in 24 hours). The GPS satellites send the microwave signals to the GPS receivers using Code Division Multiple Access (CDMA), which is further used to determine the user position and velocity [8, 27].

2.2 Global Orbiting Navigational Satellite System (GLONASS)

The GLONASS was developed by Russia in 1970. In 1984, GLONASS satellites were effectively organized and a number of GLONASS satellites were 12 until 1993. The GLONASS was completely functional in 1996 with 24 satellites, thereafter number of satellites started decreasing due to some financial issues. Only 6 to 8 satellites were remaining in 2001. In 2011, a number of satellites again increased to 24 satellites. Initially, the GLONASS was used by the military, later it was allowed for civil applications. Similar to GPS, GLONASS has three segments i.e., space segment, control segment, and user segment. The GLONASS has 24 satellites lying in three orbital planes of which 21 are active and rests are not used. The separation between orbital planes is 120 degrees; the satellites in the same orbit are separated by 45 degrees. Frequency Division Multiple Access (FDMA) and UTC time standard are used in GLONASS [8].

2.3 Galileo

In 2002, European Union (EU) decided to introduce its own navigation satellite system named Galileo with the help of European Space Agency (ESA). The first experimental satellite was launched in December 2005. The Galileo provides the services for commercial, civilian, and emergency applications. Galileo has three parts i.e., space segment, control segment, and user segment. Space segment has 30 satellites in which 3 are spare. The satellites in Galileo use different frequencies. The time scale in Galileo is Galileo System Time (GST) and signaling technique used is CDMA [9].

2.4 Compass / BeiDou

The Compass is the navigational satellite system of China, which is currently in the development phase. In 1980, China decided to build its own navigational system. In 2000, China launched BeiDou consisting of three satellites that covers whole China region. In 2012, BeiDou reached 14 operational satellites where number of satellites in GEO, MEO, and Inclined Geosynchronous Satellite Orbit (IGSO) are five, four, and five respectively to cover the Asia region only. It is expected that compass will become global in the year 2020 with 35 satellites [10].

2.5 India Regional Navigation Satellite System (IRNSS)

The IRNSS is launched by India in 2013. The IRNSS has seven satellites in which three are in geosynchronous and four are in geostationary orbits. The first satellite, IRNSS-1A, was launched in July 2013. The IRNSS position accuracy is about 20 m with coverage area of approximately 1500km [11].

2.6 Quasi-Zenith Satellite System (QZSS)

The QZSS is the Japanese regional satellite system, which is being developed by the Advanced Space Business Corporation (ASBC). The QZSS will use three satellites to cover the regions in East Asia and Oceania centering on Japan. The satellites will be placed in High Elliptical Orbit (HEO). The QZSS will use time base of GPS with similar navigation messages. The Japanese Satellite Navigation Geodetic System (JGS) will be used in QZSS [12].

3. Performance Evaluation Measures for GNSS

The performance evaluation of GNSS is indeed important to distinguish any navigational system in terms of accuracy and quality of the received data. Most commonly used evaluation measures used to validate the position provided by any GNSS are receiver positioning accuracy, DOP, SNR, and satellite visibility [14,15]. These measures are discussed in detail as follows.

3.1 Accuracy Measures

The observational data is usually validated using accuracy and precision measures. The accuracy is used to measure the closeness of the given data with respect to its true (actual) value. It is an important evaluation measure that describes the characteristics of a system and is commonly used to distinguish the performance of different systems. The positions provided by GNSS are also validated for its goodness using different accuracy measures. Whereas precision is the measure of closely estimated coordinates with respect to each other. Accuracy and precision are commonly used to define that how good is the position achieved by the receiver. Fig.1 shows the relationship between accuracy and precision [14]. In the literature, various accuracy measures are discussed and used for performance evaluation of GNSS. Different accuracy measures grouped into three broad categories are shown in Fig.2, whereas brief description of these accuracy measures is listed in Tables 1 and 2.

3.1.1 Distance Root Mean Squared (DRMS)

The DRMS is computed by calculating the standard deviations σ from the true position of the receiver in a given direction.

3.1.2 Circular Error Probability (CEP)

The CEP is the measure of the radius of a circle enclosing 50% of the position value. It is a simple method but GDOP analysis is difficult in this scenario.

3.1.3 2DRMS

The 2DRMS is the measure of the radius of a circle enclosing 95% of the position value. It is simple to calculate and helpful in GDOP analysis.

3.1.4 R95

The R95 is the measure of the radius of a circle enclosing 95% of the position value. It is simple to calculate but GDOP analysis is difficult in this scenario.

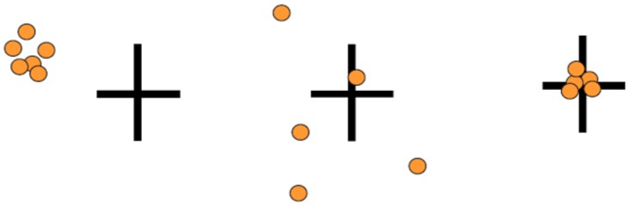


Fig. 1 An example showing difference between accuracy and precision (left) high precision, low accuracy, (middle) low precision, low accuracy, (right) high precision, high accuracy

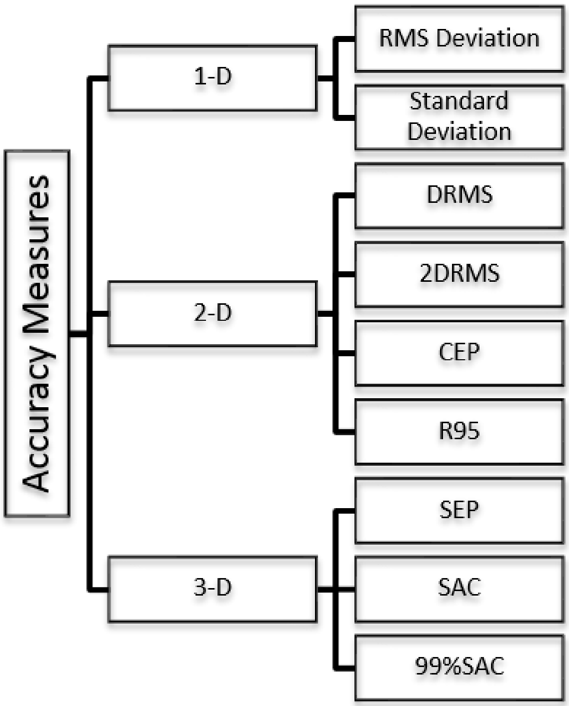


Fig. 2 Classification of different accuracy measures

Table 1: Description of 2-D accuracy measures

Accuracy Measures	***Formula***	***Definition***	***Probability***
DRMS	$\sqrt{\sigma_x^2+\sigma_y^2}$	Square root of the average of the square errors.	65%
2DRMS	$2\sqrt{\sigma_x^2+\sigma_y^2}$	Double the DRMS of the horizontal position errors.	95%
3DRMS	$3\sqrt{\sigma_x^2+\sigma_y^2}$	Three times the DRMS of the horizontal position errors.	97.5%
CEP	$0.59\,(\sigma_x+\sigma_y$	If 50% of the values occurred in the radius of the circle.	50%
R95	$0.62\sigma_x+0.56$	If 95% of the values occurred in the radius of the circle.	95%

Table 2: Description of 3-D accuracy measures

Accuracy Measures	***Formula***	***Definition***	***Proba-bility***
SEP	$0.51\,(\sigma_y+\sigma_x+\sigma_z)$	If 50% values lie in the radius of the sphere in three dimensions.	50%
MRSE	$\sqrt{\sigma_x^2+\sigma_y^2+\sigma_z^2}$	If 61% values lie in the radius of the sphere in three dimensions.	61%
SAC	$0.833\,(\sigma_y+\sigma_x+\sigma_z)$	If 90% values lie in the radius of the sphere in three dimensions.	90%
99%SAC	$1.122\,(\sigma_y+\sigma_x+\sigma_z)$	If 99% values lie in the radius of the sphere in three dimensions.	99%

3.2 Dilution of Precision

The geometry of satellites plays an important role in determining the position accuracy of any GNSS. The better reliability and accuracy is achieved by better satellite geometry and overcome the noise in the system. The satellite geometry shows the location of satellites by geometric position as seen by the receiver. It is measured by a single dimensionless number known as Geometric Dilution of Precision (GDOP) [28]. The DOP is the ratio of square root of the standard deviation of variables and pseudo range. Small GDOP values result in good positioning accuracy. To compute the receiver position, at least four satellites are required. The best satellite geometry is achieved, if the number of satellites is greater than four. When the satellites are close to each other, the area of intersection of coverage is larger that results in in poor positioning. When the satellites are placed apart, the area of intersection of coverage is low that results in good geometry (better positioning) (see Fig. 3). The GDOP is divided into two broad classes i.e., Position Dilution of Precision (PDOP) and Time Dilution of Precision (TDOP). To study the horizontal and vertical components, PDOP is further categorized into Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP). Different components of DOP are calculated as follows:

$$GDOP = \frac{\sqrt{\sigma_E^2 + \sigma_N^2 + \sigma_U^2 + \sigma_T^2}}{\sigma} \quad (1)$$

$$PDOP = \frac{\sqrt{\sigma_E^2 + \sigma_N^2 + \sigma_U^2}}{\sigma} \quad (2)$$

$$HDOP = \frac{\sqrt{\sigma_E^2 + \sigma_N^2}}{\sigma} \quad (3)$$

$$VDOP = \frac{\sigma_U}{\sigma} \quad (4)$$

$$TDOP = \frac{\sigma_T}{\sigma} \quad (5)$$

Here, σ_E^2, σ_N^2, σ_U^2 are the variances of east, north and up components of receiver position values, σ_T^2 is the variance of receiver clock. The details of DOP rating values are shown in Table 3.

Table 3: Description of DOP values

DOP value	***Quality rating***	***Remarks***
1	Ideal	Highest possible confidence achieved in position accuracy.
1-2	Excellent	Most of the measurements are accurate.
2-5	Good	Low confidence level for using position data in business applications.
5-10	Average	Measurements are adequate for some applications, however, they need improvement.
10-20	Fair	Low confidence levels. The position measurements should be used carefully.
>20	Poor	Significant levels of inaccuracies present in the position data.

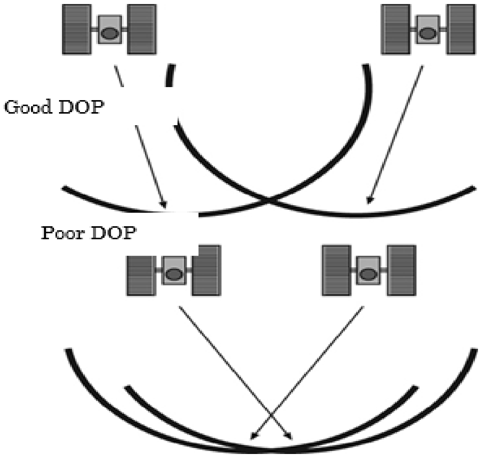


Fig. 3 Good DOP vs. Poor DOP

3.3 Signal to Noise Ratio (SNR)

To achieve the best positioning of system, a system is developed to examine the basic characteristics of the GNSS. SNR is important evaluation measure that describes the characteristics of a system and distinguishes the performance of different systems. SNR is the ratio between signal power and noise, recorded with a GNSS receiver. The accuracy of the system is directly affected by SNR [29]. The SNR varies with different parameters. Following equation describes the relation between RMS phase noise and SNRL [15, 30].

$$\sigma_\phi^2 \cong \frac{1}{SNR_L} \quad (6)$$

The noise in the antenna is generated due to electromagnetic radiations coming from sky. The noise is also generated due to other environmental factors. The shape, size, and location of the antenna also disturb the noise power. The cable losses and noise in the receiver are the source of receiver noise. The multipath effect is one of the largest sources, which results in propagation errors of the signal. It happens when the signal received at the receiver by reflecting through various surfaces. These signals when reflected are slightly shifted in time [30].

3.4 Satellite Visibility

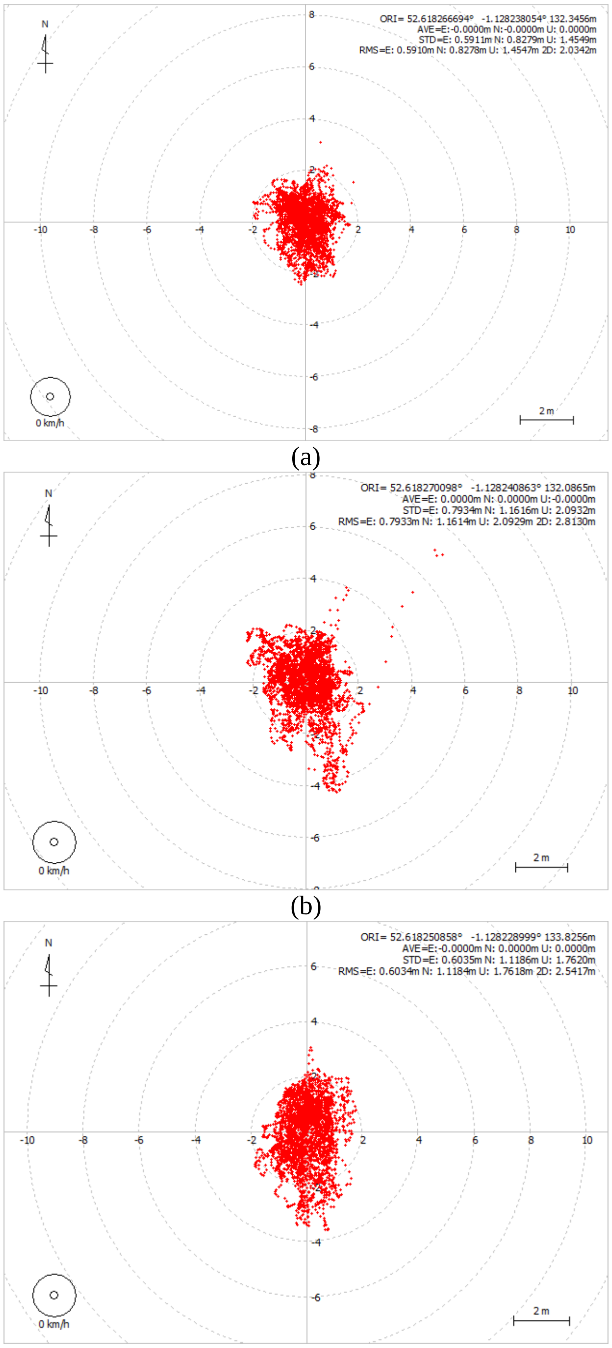
The satellite visibility is used to estimate the number of tracking satellites in a particular satellite constellation. Time of Arrival (TOA) relies on orbiting satellites to compute the position of an object [31]. The GNSS receiver position is estimated using the number of satellites tracked by the receiver from various constellations. In the following section, we discuss the experimental results.

4. Experimental Results

In this work, we compared the performance of GPS, GLONASS, and combination of both using different quality indicators. We used accuracy measures, DOP, SNR, and satellite visibility. The position data was collected by a GNSS receiver for almost 5 hours in an open urban location and is further processed by RTKLIB tool. The data is collected in Receiver INdependent EXchange (RINEX) format [32]. The scattering plots are shown in Fig. 4. From these graphs, we estimate the accuracy measures of the system and the results are shown in Table 4.

Table 4: Accuracy measures results (in meters) for GPS, GLONASS, and GPS+GLONASS (best results are in bold).

Measure	***Accuracy Probability***	***GPS***	***GLONASS***	***GPS+GLONASS***
CEP	50%	0.83	1.15	1.01
RMS	65%	1.01	1.40	1.32
2DRMS	95%	2.03	2.80	2.64
R95	95%	1.68	2.33	2.2

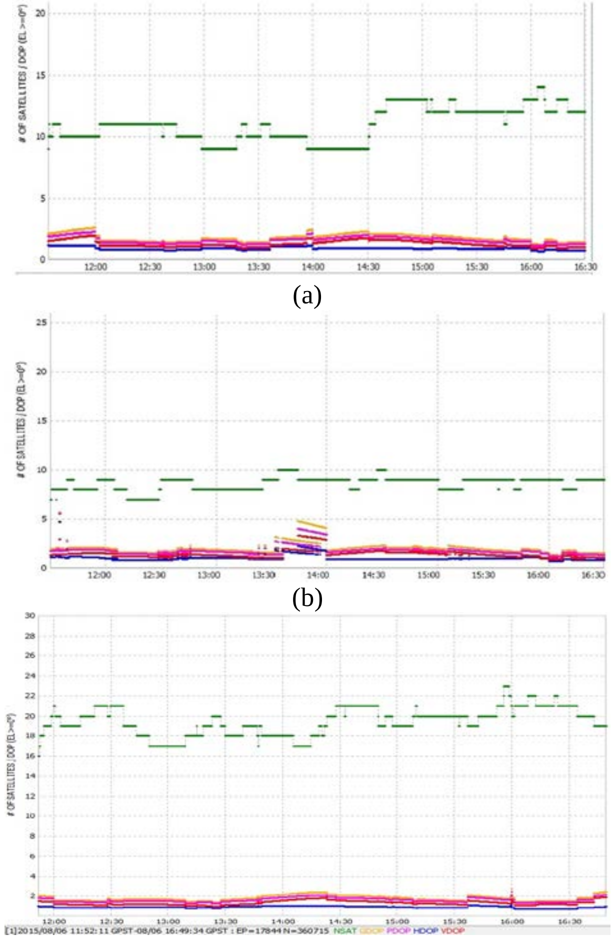


(c)

Fig. 4 Scatter plots for an open urban area, (a) GPS, (b) GLONASS, (c) GPS + GLONASS

From the results in Table 4, it is observed that integration of GPS with GLONASS degrade the accuracy as compared to GPS alone. The accuracy probability of GLONASS is larger, compared to when combined with GPS or even GPS alone in an open area. Hence it can be deduced that the inaccuracy of GLONASS have a negative impact on the positional accuracy of the receiver even though it is evident from Table 4 that the difference is not significant. Integration of GPS and GLONASS to increase the positioning reliability is, however, crucial in a way that it increases the complexity due to the difference in frequencies. A slight decline in the accuracy is also observed due to the presence of additional noise.

The number of valid connected satellites and the DOP for GPS, GLONASS, and GPS+GLONASS are shown in Fig. 5. The ratio between the root sum square of variables and standard deviation of the pseudo range is known as DOP. So the better satellite geometry is achieved with the lower value of DOP. Figure 5 illustrates the DOP with a valid number of satellites.

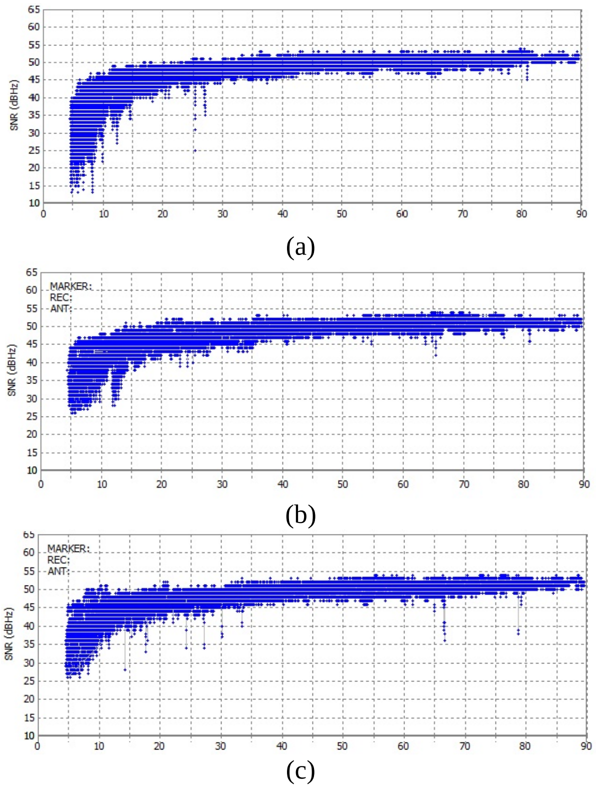


(c)

Fig. 5 Number of satellites vs. DOP for (a) GPS, (b) GLONASS, (c) GPS + GLONASS

From Fig. 5, it is observed that the DOP of GPS is in the range of 2-3 which is close to the accurate value, while DOP of GLONASS is larger than GPS, so positional accuracy of GPS is better than GLONASS and integration of both.

The SNR plots of position data for different elevation angles and for GPS, GLONASS, and GPS+GLONASS are shown in Fig. 6. From these graph we estimate the accuracy of navigational system.



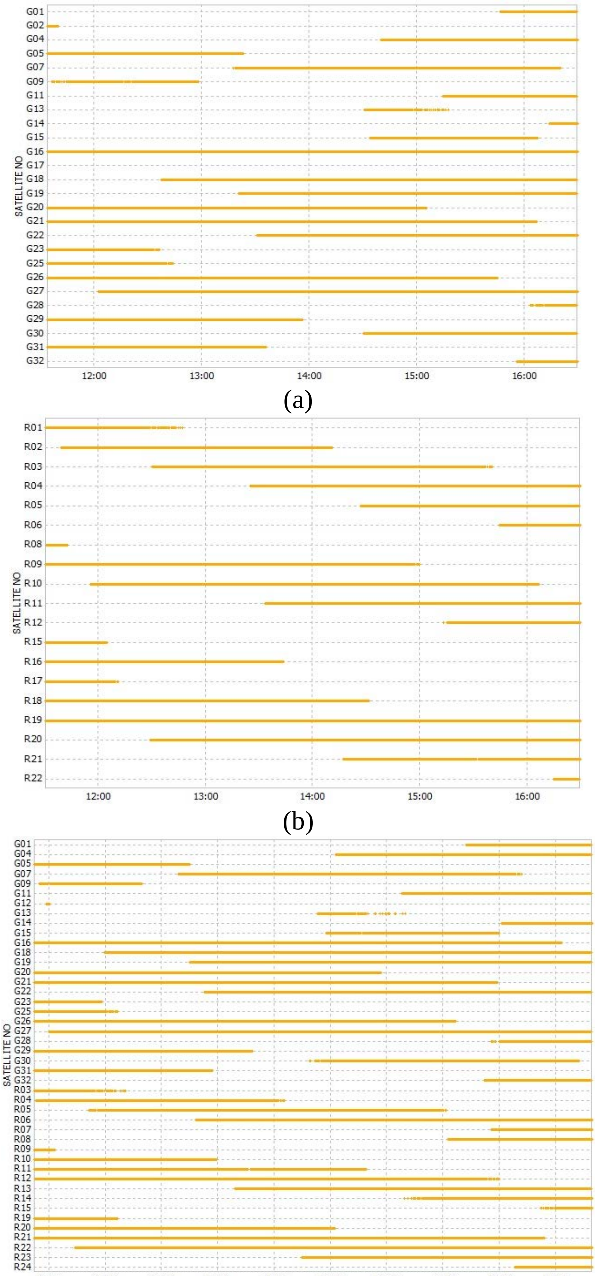
(a)

(b)

(c)

Fig. 6 SNR plot with reference to time elevation° (a) GPS, (b) GLONASS, (c) hybrid GPS + GLONASS

The SNR and elevation angle have a relationship stated that low satellite angles tends to decrease the accuracy, however at less noisy environment, the relationship between SNR is ‘almost’ directly proportional [15]. At the elevation angles less than 15° the SNR is spread and fluctuating. For GPS it goes to 15 dB and beyond 20° it starts to stabilize and keep the SNR more than 45°. SNR plots of GLONASS and its integration explain the sustainability of the behavior using either navigation satellite constellation as it keeps itself at 45 to 55 dB, the consistency can be observed in the value of SNR which stays between 45 dB to 55 dB. GPS has fewer fluctuations than GLONASS and integration of GPS and GLONASS, so GPS is the best navigation system than GLONASS and GPS+GLONASS. The GNSS receiver position is estimated using the number of visible satellites and number of satellites tracked from different constellations. In this paper, the visibility of GPS, GLONASS, and GPS+GLONASS satellites over the period of 5 hours is determined and shown in Fig. 7. From Fig. 7, we estimate the visible satellites and how many satellites are tracked. From these plots, we observe that in GLONASS, the number of satellites is greater than GPS, while in GPS+GLONASS the number of satellites is greater than GPS and GLONASS.



(a)

(b)

(c)

Fig. 7 Satellite visibility plots (a) GPS, (b) GLONASS, (c) hybrid GPS + GLONASS

5. Conclusion

In this paper, we presented the performance evaluation of different navigation satellite systems, namely GPS, GLONASS and hybrid GPS+GLONASS, by applying different accuracy measures. The real data was collected in the capital city of Pakistan. The data used was in RINEX format, which was further processed by a RTKLIB. The performance was evaluated using four different measures; accuracy, DOP, SNR, and visibility. The results showed that SNR, DOP, and positional accuracy of GPS are very close to perfect value. The SNR of GPS has fewer fluctuations than GLONASS and GPS+GLONASS. The DOP value of GPS is lower than GLONASS and GPS+GLONASS, which result in best satellite geometry of GPS alone. The positioning accuracy of GPS alone is ideal rather GLONASS and GPS- GLONASS. When GPS is integrated with GLONASS, positional accuracy is improved than that of GLONASS. Therefore, it is concluded that GPS performance is better than GLONASS and GPS+GLONASS.

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