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Relative Positioning of Autonomous Ground Vehicles Combining Multi-GNSS (GPS-L1, GLONASS-G1 and BDS-B1) Observations

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Abstract: To perform to their full capacity, Autonomous Ground Vehicles (AGV) require a powerful, dependable, and precise navigation system. Optical, inertial, signals-of-opportunity (SOPs), standalone and augmented Global Navigation Satellite System (GNSS), and other modern technologies are used to construct such a system. In fact, the AGV navigation system heavily relies on the usage of GNSS. The key threats or errors of GNSS codHane and carrier phase observations include clock error, orbit error, ionospheric delay, and tropospheric delay. By minimising the errors and employing a relative positioning approach, an AGV may be positioned precisely. When using carrier phase observations, relative location precision up to the cm level is possible. The accuracy of relative position using GPS-L1, GLONASS-G1, BDS-B1, and GPS/BDS/GLONASS integrated system signals for AGV applications is therefore examined in this study work. A software-based framework is also developed to analyse the data and produce relative positioning results.

Keywords: *Autonomous Ground Vehicles, GNSS, relative positioning*

1. Introduction

There is a lot of research being done, especially to provide accurate positioning, to improve the accuracy and dependability of autonomous vehicle and intelligent transportation system (ITS) technology. The location of autonomous vehicle is done using the most sophisticated technology available: the Global Navigation Satellite System (GNSS). It offers worldwide precise location services using signals provided by a network of satellites orbiting the Earth [Swamy, 2017]. However, multipath, orbit errors, ionospheric delay, tropospheric delay, and satellite clock bias reduce the GNSS position accuracy. According to studies reported, using multiple constellations in combination increases position accuracy, precision, availability, and reliability [Luca Poluzzi et al. 2021]. When GPS and BDS are combined, there are more visible satellites and the location accuracy is higher than with just one GNSS system. However, it should be noted that in a situation like an urban canyon, satellite visibility may be inadequate or even multipathing may occur. The relative accuracy of location using GPS and BDS in the actual road environment must thus be analysed [Jae Hee Noh et al., 2019]. The dependability of positioning solutions is increased by using BDS in addition to GPS and GLONASS. Additionally, a multi-GNSS system enhances the geometry of the satellites that are visible, increasing positioning accuracy [Jiao et al. 2012]. Additionally, a combined system would enable the use of high elevation cut-off and expand the application of GNSS in restricted areas with low-level multipath [Han et al.2018, Kaloop et al.2020].

Comprehensive RDSS positioning has become an important research direction of global satellite navigation to improve the ratio of cost and efficiency, reduce the user machine complexity and improve the positioning accuracy [Cao et al. 2013]. Adding BDS observations can contribute to accelerating the convergence speed of Precise Point Positioning (PPP). The convergence time can be reduced by 10 – 12% for GPS PPP, and 5-7% for GPS/GLONASS

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PPP after adding BDS observations [P. Li and X. Zhang 2014]. Combined GPS/GLONASS/BDS positioning proves that the accuracy of triple-system positioning is better than that of the single or double system [Yize et al. 2014]. Further, quad-constellation (GPS, BeiDOU, GLONASS and GALILEO) kinematic PPP significantly improves the positioning accuracy and convergence time in comparison with the single-constellation and double-constellation [Cai et al. 2015].

Relative positioning is the process of figuring out a receiver's location in relation to another receiver or a known location on the surface of the Earth. The time-of-flight of the signals sent by the satellites can be used to calculate the distance between the receivers. GPS, GLONASS, and BDS are the three primary GNSS systems that can be used to determine relative location. However, the inaccuracies in code and carrier phase measurements are being eliminated by the double-differenced method [Swamy et al., 2022; Swamy et al., 2023]. The relative positioning system (RPS) explores the signal properties over a large spectrum of frequency bands, and derives a vehicle tracking algorithm to accurately estimate the vehicle’s trajectory in space and time using an arbitrary set of unknown reference positions. Also, studies reported relative positioning using single and multiple constellations [Euiho Kim, 2021; Magalhaes et al, 2021; de Souza et al., 2009].

In this paper, GPS L1, GLONASS G1, and BDS B1 observations are utilized to examine the performance of relative positioning results. Two Septentrio receivers were employed to collect the data of GPS-L1, GLONASS-G1, and BDS-B1 signals. Finally, precise relative positioning is accomplished via a software-based platform (RTKLIB).

2. Relative positioning with Degree of Precision

Relative positioning is a method for fixing the location of one receiver in respect to another with centimetre-level accuracy. This approach uses carrier phase data from two or more GNSS receivers to resolve integer ambiguities. When the integer ambiguities are resolved, the relative position between the receivers will be more accurate. The concept of relative positioning can also be adopted for precise location of AGV.

In Sections 2.1 and 2.2, we discussed the properties of the GPS, GLONASS, and BDS signals and the method of precise relative position using those signals.it.

2.1. Characteristics of Signals

GPS, GLONASS and BDS are three different Global Navigation Satellite Systems, each of them have their own unique characteristics.

Global Positioning System (GPS)

The GPS system is supported by a constellation of 24 satellites in Medium Earth Orbit (MEO). It uses L1, L2 and L5 frequencies (1575.42 MHz, 1227.60 MHz, and 1176.45 MHz, respectively) to transmit the ranging signals with code division multiple access (CDMA) technique to the multiple users. GPS signals employs two codes, C/A and P-code. The C/A code is used for civilian applications and P code is used for military applications [Misra and Enge; 2006].

Global Navigation Satellite System (GLONASS)

The GLONASS constellation consists of 24 MEO satellites, transmit signals on L1 (1598.06 – 1604.40 MHz) and L2 (1242.94–1248.63 MHz) frequencies with frequency division multiple access (FDMA).

BeiDou Navigation Satellite System (BDS)

BeiDou constellation consists of MEO and inclined geosynchronous orbit (IGSO) satellites, they transmit B1 (1561.098 MHz), B2 (1207.140 MHz), and B3 (1268.520 MHz) frequencies with FDMA. The BDS civilian signal are B1I, B1Q, B2I and B2Q. B1C and B2A are military signals.

2.2. Relative Positioning using Single Constellation

Relative positioning method uses code/carrier phase observations as well as double-difference code/carrier phase observations for precise positioning. The mathematical equations for double-difference carrier phase observations and double-difference code observations of GPS, GLONASS, and BDS for short baseline length are Eqs. (1-6).

The double-difference of code observations for GPS is,

$$\Delta\nabla P^{ij}_{L1,ru} = \Delta\nabla\rho^{ij}_{L1,ru} + \Delta\nabla\in^{ij}_{\phi_{L1},ru} \quad (1)$$

The double-difference of code observations for GLONASS is,

$$\Delta\nabla P^{ij}_{G1,ru} = \Delta\nabla\rho^{ij}_{G1,ru} + \Delta\nabla\in^{ij}_{\phi_{G1},ru} \qquad (2)$$

The double-difference of code observations for BDS is,

$$\Delta\nabla P^{ij}_{B1,ru} = \Delta\nabla\rho^{ij}_{B1,ru} + \Delta\nabla\in^{ij}_{\phi_{B1},ru} \qquad (3)$$

The double-difference of carrier phase observations for GPS is,

$$\boldsymbol{\lambda}_{L1}\Delta\nabla\phi^{ij}_{L1,ru} = \Delta\nabla\rho^{ij}_{L1,ru} + \boldsymbol{\lambda}_{L1}\Delta\nabla N^{ij}_{L1,ru} + \boldsymbol{\lambda}_{L1}\Delta\nabla\in^{ij}_{L1,ru} \qquad (4)$$

The double-difference of carrier phase observations for GLONASS is,

$$\boldsymbol{\lambda}_{G1}\Delta\nabla\phi^{ij}_{G1,ru} = \Delta\nabla\rho^{ij}_{G1,ru} + \boldsymbol{\lambda}_{G1}\Delta\nabla N^{ij}_{G1,ru} + \boldsymbol{\lambda}_{G1}\Delta\nabla\in^{ij}_{G1,ru} \qquad (5)$$

The double-difference of carrier phase observations for BDS is,

$$\boldsymbol{\lambda}_{B1}\Delta\nabla\phi^{ij}_{B1,ru} = \Delta\nabla\rho^{ij}_{B1,ru} + \boldsymbol{\lambda}_{B1}\Delta\nabla N^{ij}_{B1,ru} + \boldsymbol{\lambda}_{B1}\Delta\nabla\in^{ij}_{B1,ru} \qquad (6)$$

In the above equations, “ϵ” is residual errors, “λ_{L1}” GPS-L1 signal wavelength, “λ_{G1}” GLONASS-G1 signal wavelength, “λ_{B1}” BDS-B1 signal wavelength. Super scripts indicates the satellites, whereas ‘r’ and ‘u’ stands for the reference station and the user, respectively. The linear model using double-difference observations is given in Eq. (7),

$$y = \begin{bmatrix} \rho_P \\ \rho_\phi \end{bmatrix} = \begin{bmatrix} G_u(t) & 0 \\ G_u(t) & \lambda I_{n-1} \end{bmatrix} \begin{bmatrix} \tilde{x}(t) \\ N_u \end{bmatrix} + \epsilon \qquad (7)$$

Where $\tilde{x}(t)$ is a linear model’s unobserved variable. The receiver position and the receiver clock error are two examples of the parameters of unknown variables. Where $\tilde{x}(t)$ is described as,

$\tilde{x}(t) = [x \quad y \quad z \quad \delta t]$.
(8)

3. Experimental Results

In this research work, we collected GPS-L1, GLONASS-G1 and BDS-B1 observations using the Patch antenna and two Septentrio receivers at short baseline length with 10° elevation mask angle, the setup of the field experiment is depicted in Figure. 1. Here, one receiver is assumed as reference station and another receiver is assumed as AGV.

Fig.1. Relative positioning field experimental setup

In Section 3.1, we looked at the satellites visibility while they were visible in the open sky. The relative positioning accuracy results based on the three constellation’s observations were presented in section 3.2. The accuracy of relative positions was also examined while the number of GPS, GLONASS and BDS visible satellites was at its lowest.

3.1. Satellite Visibility and Relative Positioning

The number of visible satellites play a crucial role in achieving precise positioning through satellite systems such as GPS, GLONASS, and BDS. When determining the receiver’s position, more satellites are needed to provide accurate observations and improved geometric configuration of the system. Having a higher number of satellites increases the availability of signal sources for the receiver. The availability enables the receiver to receive signals from different satellites at various positions in the sky. With more satellites in view, the receiver has a greater opportunity to calculate accurate positioning information.

Figure 2 shows the number of GPS, GLONASS and BDS satellites that are visible at 10° elevation mask angle. Currently, there are 8–10 satellites of GPS, 5–9 satellites of GLONASS, and 14–16 satellites of BDS are visible. The dual integrated systems used here are GPS/GLONASS, GPS/BDS and GLONASS/BDS. These combinations provide users with a wider range of visible satellites, leading to improved performance. The number of visible satellites for the dual integrated systems GPS/GLONASS, GPS/BDS, and GLONASS/BDS are 13–19, 23–26, and 17–24 respectively. The GPS/GLONASS/BDS integrated system provides the most visible satellites, with a range of 23 to 30, making it the ideal combination of satellite systems. The increased numbers of visible satellites contribute to a more robust geometric arrangement and improved accuracy in precise positioning calculations for the receiver.

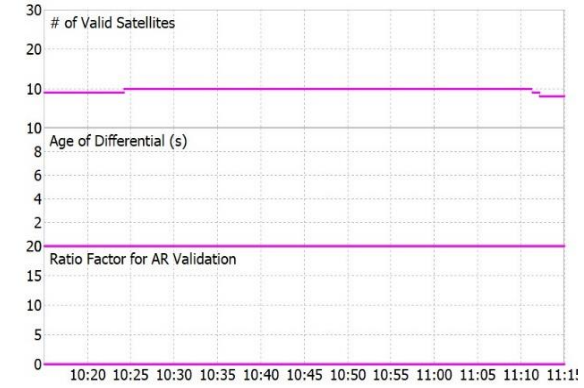

Fig.2a: The total count of GPS satellites that are observed.

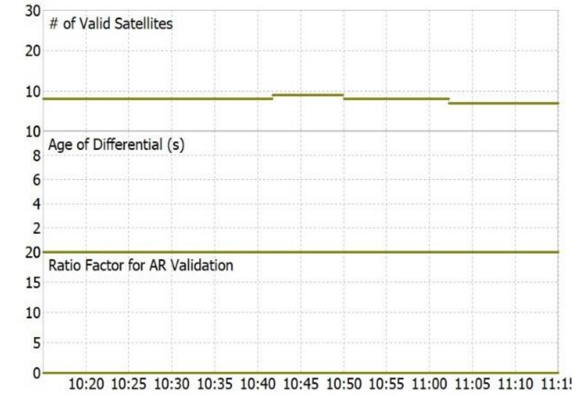

Fig.2b: The total count of GLONASS satellites that are observed.

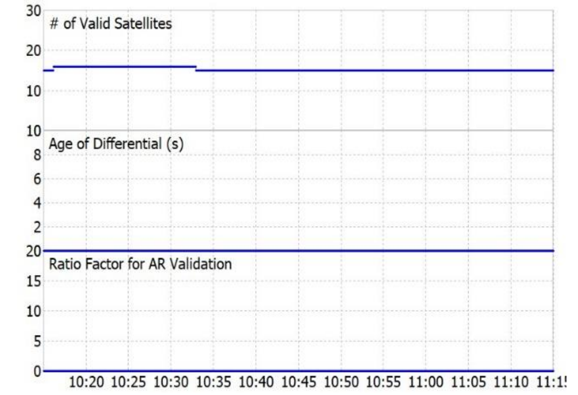

Fig.2c: The total count of BDS satellites that are observed.

Fig 2. The total number of visible satellites for different constellations

The relative positioning of a vehicle using GPS-alone, GLONASS-alone, BDS-alone, and the dual integrated systems GPS/GLONASS, GPS/BDS, GLONASS/BDS, and GPS/GLONASS/BDS integrated system between 10:15 (UTC + 05:30) and 11:15 (UTC + 05:30) is displayed in Figures. 3 through 5.

The terms AVG, STD, and RMS stands for the average, standard deviation, and root mean square respectively. AVG influences the accuracy of triangulation calculations, STD affects positioning by reducing scatter and improving the precision of satellite position estimates. RMS contributes to precise positioning by reducing positional errors, leading to higher overall accuracy in determining the position of ground systems.

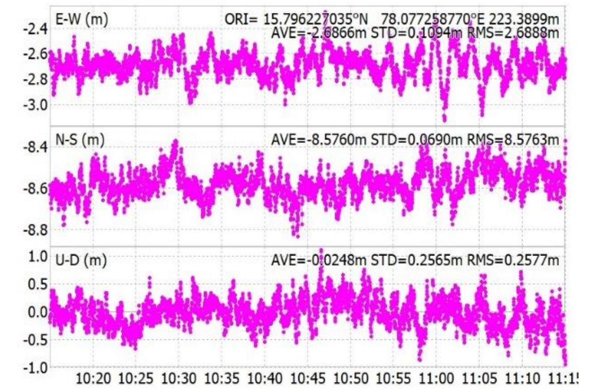

Fig.3a: Relative position accuracy GPS-alone satellite

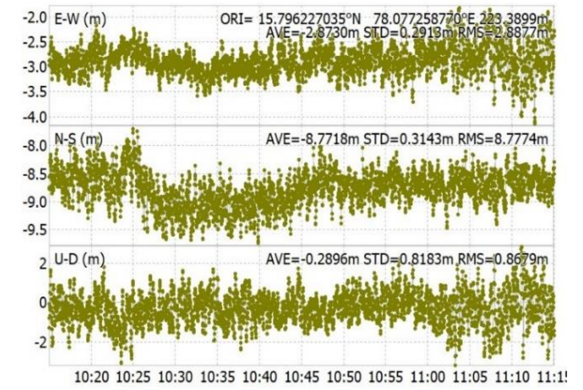

Fig.3b: Relative position accuracy GLONASS-alone satellite

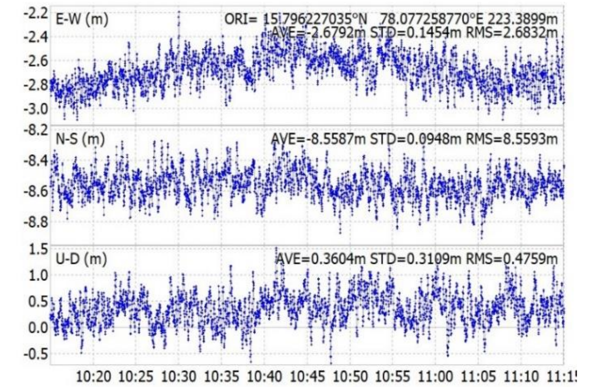

Fig.3c: Relative position accuracy BDS-alone satellite

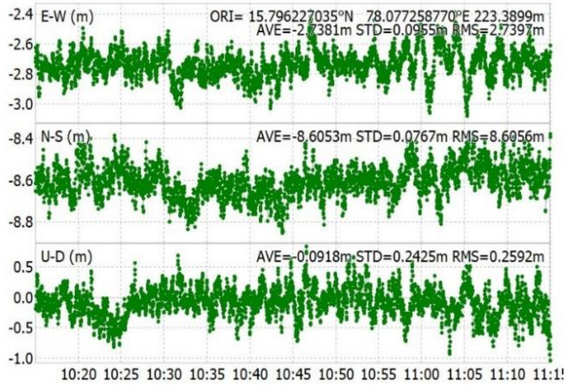

Fig.4a: Relative position accuracy of integrated system GPS/GLONASS satellites

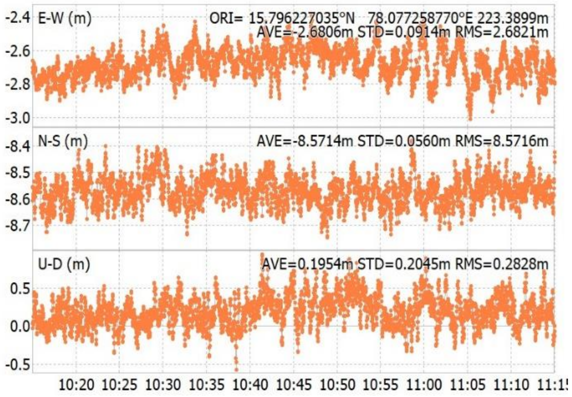

Fig.4b: Relative position accuracy of integrated system GPS/BDS satellites

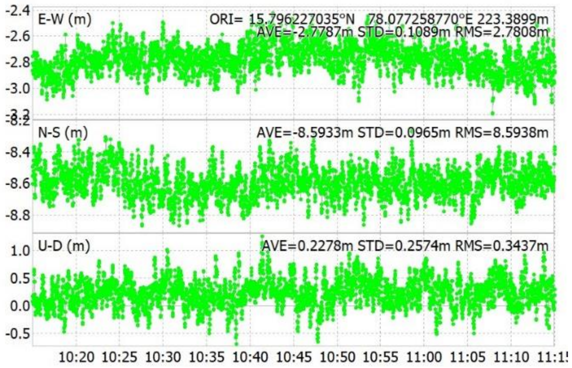

Fig.4c: Relative position accuracy of integrated system GLONASS/BDS satellites.

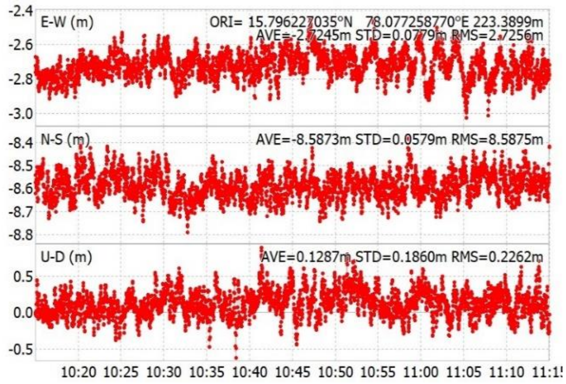

Fig.5: Relative position accuracy of integrated systems GPS/GLONASS/BDS

Fig 3-5. Relative position accuracy of single and multiple constellations

Table.1 shows the AVG, STD, and RMS of different constellations, E-W is the East to West direction, N-S indicates the North-South direction, and U-D represents the Up-Down direction of the satellite orientation. From the results it is observed that the BDS is characterized by lower STD (standard deviation) and RMS (root mean square) values compared to GLONASS. This suggests that BDS provides more accurate positioning information due to reduced measurement errors. Additionally, using a dual integrated system, which combines observations from multiple satellite constellations, improves accuracy compared to relying solely on single satellite systems. Incorporating observations from two systems, such as GPS/GLONASS, GPS/BDS, and GLONASS/BDS, satellite availability increases and geometric dilution of precision (GDOP), enhances resulting in improved relative positioning accuracy for autonomous ground vehicles.

Furthermore, a three-system integrated configuration, which includes three satellite constellations (GPS/GLONASS/BDS), further enhances precision by mitigating limitations and increasing the overall number of available satellites. These factors collectively contribute to more precise and reliable relative positioning of autonomous ground vehicles.

Table 1. AVG, STD, and RMS of the satellite systems

Satellite system	Position	AVG	STD	RMS
GPS	E-W	-2.6866	0.1094	2.6888
	N-S	-8.5760	0.0690	8.5763
	U-D	-0.0248	0.2565	0.2577
GLONASS	E-W	-2.8730	0.2913	2.8877
	N-S	-8.7718	0.3143	8.7774
	U-D	-0.2896	0.8183	0.8679
BDS	E-W	-2.6792	0.1454	2.6832
	N-S	-8.5587	0.0948	8.5593
	U-D	0.3604	0.3109	0.4759
GPS/GLONASS	E-W	-2.7381	0.0955	2.7397
	N-S	-8.6053	0.0767	8.6056
	U-D	-0.0918	0.2425	0.2592
GPS/BDS	E-W	-2.6806	0.0914	2.6821
	N-S	-8.5714	0.0560	8.5716
	U-D	0.1954	0.2045	0.2828
GLONASS/BDS	E-W	-2.7787	0.1089	2.7808
	N-S	-8.5933	0.0965	8.5938
	U-D	0.2278	0.2574	0.3437
GPS/GLONASS/BDS	E-W	-2.7245	0.0779	2.7256
	N-S	-8.5873	0.0579	8.5875
	U-D	0.1287	0.1860	0.2262

3.2. DOP Results

The Dilution of Precision (DOP) plays a crucial role in assessing the accuracy of satellite positioning systems. DOP values are influenced by factors such as the number and arrangement of satellites in view, their positions relative to other, and the geometry of the receiver's location.

Figure 6 through 12 shows the NSAT, PDOP, GDOP, HDOP, VDOP of GPS, GLONASS, BDS, and the dual integrated systems- GPS/GLONASS, GPS/BDS, GLONASS/BDS and the three-system GPS/GLONASS/BDS at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30). The corresponding results are displayed in the Table.2

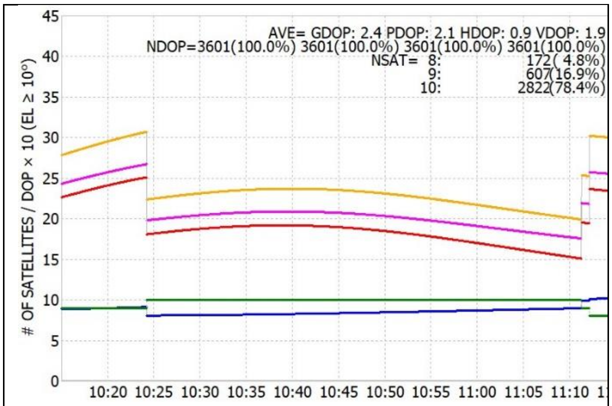

Fig.6: NSAT (Green), PDOP (Pink), GDOP (Orange), HDOP (Blue), VDOP (Red) at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30) of GPS

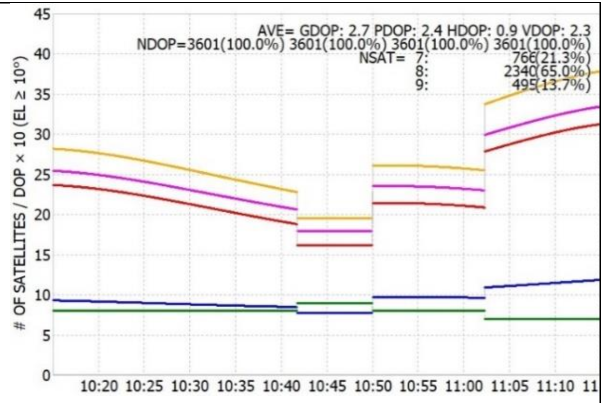

Fig.7: NSAT (Green), PDOP (Pink), GDOP (Orange), HDOP (Blue), VDOP (Red) at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30) of GLONASS

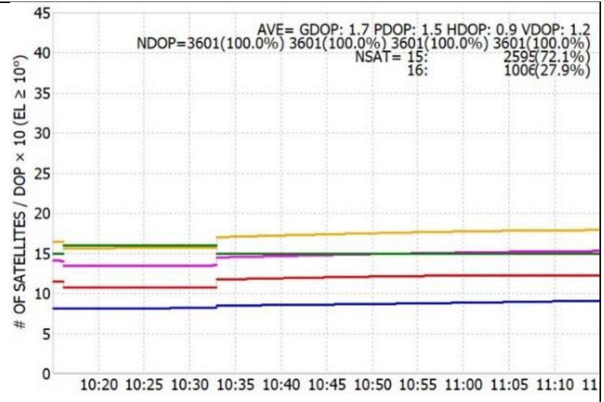

Fig.8: NSAT (Green), PDOP (Pink), GDOP (Orange), HDOP (Blue), VDOP (Red) at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30) of BDS

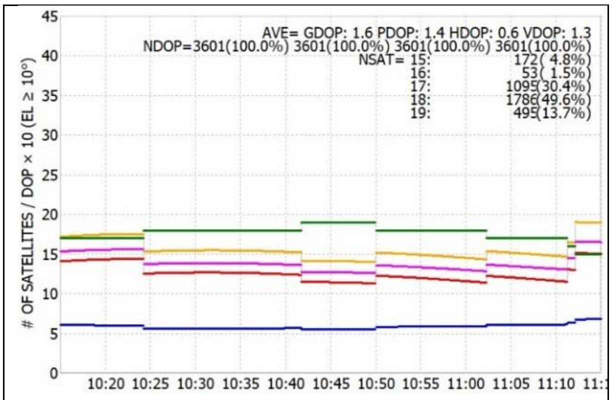

Fig.9: NSAT (Green), PDOP (Pink), GDOP (Orange), HDOP (Blue), VDOP (Red) at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30) of GPS/GLONASS

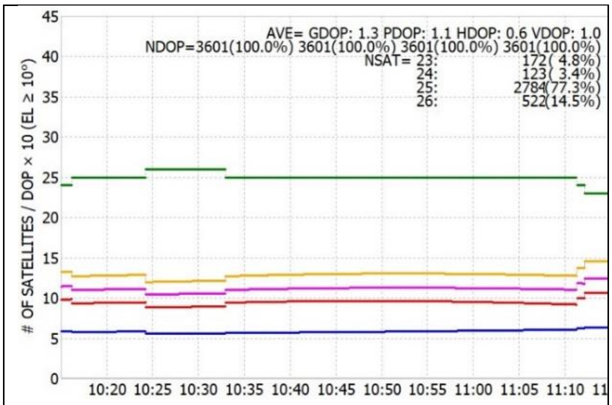

Fig.10: NSAT (Green), PDOP (Pink), GDOP (Orange), HDOP (Blue), VDOP (Red) at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30) of GPS/BDS

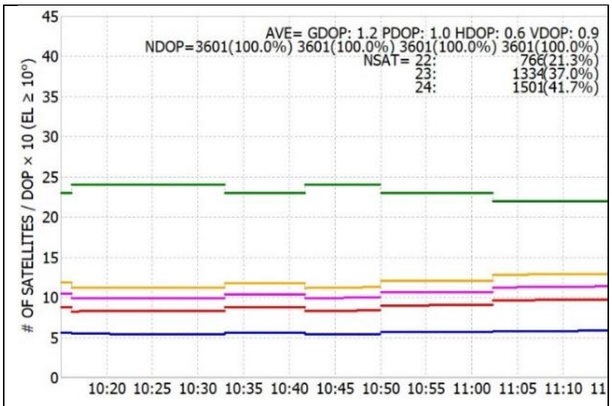

Fig.11: NSAT (Green), PDOP (Pink), GDOP (Orange), HDOP (Blue), VDOP (Red) at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30) of GLONASS/BDS

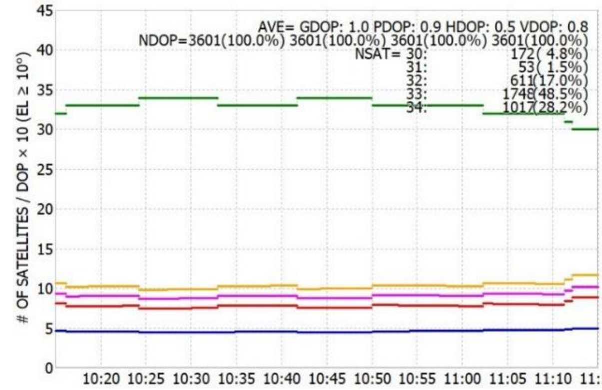

Fig.12: NSAT (Green), PDOP (Pink), GDOP (Orange), HDOP (Blue), VDOP (Red) at 10:15 (UTC + 05:30) – 11:15 (UTC + 05:30) of GPS/GLONASS/BDS

Fig 6-12: No. of satellites (NSAT) and DOP variations for single and multiple constellations

When we consider a single satellite system, GLONASS tends to have higher GDOP values compared to BDS. This implies that GLONASS, on its own, may have a less favorable geometric configuration of satellites, leading to reduce accuracy in determining the receiver’s position.

The performance of a satellite positioning system can significantly improve when multiple-GNSS systems. By combining the observations from different satellite constellations, the receiver can access a larger number of satellites, resulting in more diverse and favorable geometric arrangement. This enhanced geometric configuration translates into lower GDOP values, indicating a higher accuracy in determining the receiver’s position. On the other side, integrating multiple satellite systems provide redundancy and resilience to the positioning solution. In case of signal blockage or outages from one satellite system, the receiver can rely on signals from the other systems to maintain accurate positioning. This robustness enhances the overall performance and reliability of the satellite positioning system.

Table 2. Challenges and Solutions techniques

Satellite system	**NSAT**	**PDOP**	**GDOP**	**HDOP**	**VDOP**
GPS	8-10	2.1	2.4	0.9	1.9
GLONASS	7-9	2.4	2.7	0.9	2.3
BDS	15-16	1.5	1.7	0.9	1.2
GPS/GLONASS	15-19	1.4	1.6	0.6	1.3
GPS/BDS	23-26	1.1	1.3	0.6	1.0
GLONASS/BDS	22-24	1.0	1.2	0.6	0.9
GPS/GLONASS/BDS	30-34	0.9	1.0	0.5	0.8

4. Conclusion

In this study, the accuracy of relative position of GPS-alone, GLONASS-alone, BDS-alone, GPS/GLONASS, GPS/BDS, GLONASS/GLONASS, and GPS/GLONASS/BDS was examined. The combination of GPS, GLONASS, and BDS enhances both the number of satellites and the precision of positioning. The relative position due to GPS/GLONASS/BDS integrated systems have higher positioning precision than GPS-only, GLONASS-only, BDS-only, and both- GPS/GLONASS, both-GPS/BDS, and both-GLONASS/BDS systems. We looked at the number of GPS, GLONASS, and BDS satellites that were visible in India for a full day and the accuracy of their relative positions. In conclusion, several factors play a crucial role in autonomous vehicles relative positioning using satellite-based systems. The number of available satellites generally leads to better positioning accuracy and robustness. We observe that the three-system, GPS/GLONASS/BDS has relatively more number of satellites (30-34) than the dual integrated and single satellite systems which leads to better positioning accuracy and robustness, as it allows for a more diverse and redundant set of observations to be utilized. Lower standard deviation and RMS values signify higher precision and accuracy in satellite position estimations. The multi-GNSS system (GPS/GLONASS/BDS) has the lower DOP values (PDOP, GDOP, HDOP, and VDOP) compared to dual integrated and single GNSS systems. Ultimately, a combination of more satellites, lower DOP values, and lower STD and RMS values leads to more reliable and accurate relative positioning, reducing errors and uncertainties. However, the specific impact may vary based on the positioning system and environmental conditions.

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