Satellite Availability and Service Performance Evaluation for Next-Generation GNSS, RNSS and LEO Augmentation Constellation

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Abstract: Positioning accuracy is affected by the combined effect of user range errors and the geometric distribution of satellites. Dilution of precision (DOP) is defined as the geometric strength of visible satellites. DOP is calculated based on the satellite broadcast or precise ephemerides. However, because the modernization program of next-generation navigation satellite systems is still under construction, there is a lack of real ephemerides to assess the performance of next-generation constellations. Without requiring real ephemerides, we describe a method to estimate satellite visibility and DOP. The improvement of four next-generation Global Navigation Satellite Systems (four-GNSS-NG), compared to the navigation constellations that are currently in operation (four-GNSS), is statistically analyzed. The augmentation of the full constellation the Quasi-Zenith Satellite System (7-QZSS) and the Navigation with Indian Constellation (11-NavIC) for regional users and the low Earth orbit (LEO) constellation enhancing four-GNSS performance are also analyzed based on this method. The results indicate that the average number visible satellites of the four-GNSS-NG will reach 44.86, and the average geometry DOP (GDOP) will be 1.19, which is an improvement of 17.3% and 7.8%, respectively. With the augmentation of the 120-satellite mixed-orbit LEO constellation, the multi-GNSS visible satellites will increase by 5 to 8 at all latitudes, while the GDOP will be reduced by 6.2% on average. Adding 7-QZSS and 11-NavIC to the four-GNSS-NG, 37.51 to 71.58 satellites are available on global scales. The average position DOP (PDOP), horizontal DOP (HDOP), vertical DOP (VDOP), and time DOP (TDOP) are reduced to 0.82, 0.46, 0.67 and 0.44, respectively.

Keywords: dilution of precision; satellite availability; next-generation GNSS; RNSS; LEO augmentation

1. Introduction

In highly obstructed environments or polar regions, satellite visibility decreases significantly, which results the performance of the Global Navigation Satellite System (GNSS) service being strongly degraded [1,2]. To improve satellite availability and positioning accuracy, four-GNSS, represented by the Global Positioning System (GPS), the BeiDou Navigation Satellite System (BDS-3), the Galileo Navigation Satellite System (Galileo), and the Global Navigation Satellite System (GLONASS), have created modernization programs to upgrade these features [3,4]. The GPS has been deploying new satellites (GPS III) since the beginning of 2018. The next-generation GPS will be compatible with other international GNSS [5–7]. For the next-generation system, BDS is evaluating the feasibility of adding a low Earth orbit (LEO) augmentation constellation [8] and expects to improve the performance in the Arctic region [9,10]. GLONASS plans to create a high-orbit space segment to improve performance in difficult conditions where a spacecraft is visible at more than 25° above the horizon [11,12]. In addition, studies of the Galileo second generation constellation are ongoing [3]. The next-generation Galileo satellites will gradually join the existing constellation and reach full operational capability in 2030 [13,14]. Once the next-generation GNSS is fully deployed, there is potential for position accuracy to significantly improve due to the increased number of visible satellites and the better geometric distribution of...
the satellites [15], especially in complex urban environments and the Arctic region [16]. Moreover, the reliability of GNSS positioning can be enhanced for the higher measurement redundancy [17].

The performance of positioning and navigation depends on the user range error (URE) and the geometric distribution of satellites [18]. The standard positioning accuracy is given based on a certain percentage of time [19]. However, the actual positioning accuracy varies at different observation points or times. This variability is mainly affected by the geometric distribution of the satellites [19,20]. Dilution of precision (DOP), a geometric factor, is used to signify the geometric strength of observations and evaluates the effectiveness of potential measurements [16,21]. Multiplying the range errors with DOP provides positioning and time accuracy [20]. Many efforts have been made with DOP, including preciseness analysis [20], GNSS DOP evaluation [16,17,22], the change of DOP [23–25], and satellite selection [26–28].

The works cited above are based on the satellite broadcast or precise ephemerides, which are used to calculate the satellite position. However, because the modernization program of each system is still under construction, using the observation-based method is difficult when trying to assess the performance of the next-generation GNSS, as it lacks real ephemerides. Wang et al. [29] presented a method that does not require real ephemerides to analyze the dependency of GPS DOPs on station location. Then, Wang et al. [30] modified this method to assess the DOPs of BDS-3. Moreover, Meng et al. [31] used this method to estimate BDS DOPs with different constellation configurations. However, none of them analyzed the performance of four-GNSS constellations.

In this work, we use a well-known method by Wang et al. [29], and we modify it in such a way to calculate the satellite visibility and DOPs of next-generation four-GNSS (four-GNSS-NG) in the absence of data on the real ephemeris of future satellites. By making these estimations, we show the contribution of the next-generation constellations to navigation and positioning services. In addition, the augmentation of two regional navigation satellite systems (RNSSs), the Japanese Quasi-Zenith Satellite System (QZSS) and the Navigation with Indian Constellation (NavIC) for regional users and the LEO enhancing four-GNSS performance are also analyzed based on this method. In other words, we perform modeling to evaluate the performance of next-generation GNSSs, RNSSs, and the LEO augmentation for constellations on the global scale, demonstrating its superiority to the navigation constellations that are currently in operation.

2. Methods
2.1. Satellite Observation Probability
2.1.1. Medium and Low Earth Orbit Satellites

Medium Earth orbit (MEO) satellites, which are in approximately circular orbits, move around the whole world over time. In the Earth-centered Earth-fixed (ECEF) system, the angular velocity \( \omega_{ij} \) of an MEO satellite at \((\lambda_i, \phi_j)\) can be expressed as the following [29–31]:

\[
\begin{align*}
\omega_{\phi_j} &= \omega_{ij} \sqrt{1 - \left(\frac{\cos i_{\text{orb}}}{\cos \phi_j}\right)^2} \\
\omega_{\lambda_i} &= \omega_{ij} \frac{\cos i_{\text{orb}}}{\cos \phi_j} - \omega_e
\end{align*}
\]

(1)

where \( \lambda_i \) is the geocentric longitude, and \( \phi_j \) is the geocentric latitude; \( \omega_{\phi_j} \) and \( \omega_{\lambda_i} \) are angular velocities in the north–south directions and in the east–west directions, respectively; \( i_{\text{orb}} \) is the satellite orbit inclination; and \( \omega_e \) is the rotational angular velocity of the Earth.

Wang et al. [29] suggested that the larger the angular velocity of an MEO satellite at \((\lambda_i, \phi_j)\), the smaller observed probability will be. However, due to the convergence of the orbits towards northern and southern latitudes, the observation probability of an MEO
satellite $P_M$ is a function of $\omega_{\phi_j}$ only, which is verified by Wang et al. [30]. Thus, $P_M$ at $(\lambda_i, \phi_j)$ can be expressed as:

$$P_M(\lambda_i, \phi_j) = \frac{\kappa}{\omega_{\phi_j}}$$

(2)

Nevertheless, an MEO satellite cannot be observed when the $\phi_j$ is larger than the orbit inclination $i_{\text{orb}}$; thus, we modified $P_M(\lambda_i, \phi_j)$ as:

$$P_M(\lambda_i, \phi_j) = \begin{cases} \frac{\kappa}{\omega_{\phi_j}} & |\phi_j| < i_{\text{orb}} \\ 0 & |\phi_j| \geq i_{\text{orb}} \end{cases}$$

(3)

To calculate the constant $\kappa$ in Equation (3), the spherical orbit surface of MEO satellites can be divided into $1^\circ \times 1^\circ$ grids by $\lambda_i$ and $\phi_j$. Then, the observation probabilities for the MEO satellites for grids satisfy:

$$\sum_{\lambda_i=1}^{360} \sum_{\phi_j=-89}^{90} P_M(\lambda_i, \phi_j) = n_{\text{MEO}}$$

(4)

where $n_{\text{MEO}}$ is the total number of MEO satellites.

The law of LEO satellite motion is similar to that of MEO, the observation probabilities of the LEO satellites $P_L(\lambda_i, \phi_j)$ can also be expressed as Equation (3) and satisfy:

$$\sum_{\lambda_i=1}^{360} \sum_{\phi_j=-89}^{90} P_L(\lambda_i, \phi_j) = n_{\text{LEO}}$$

(5)

where $n_{\text{LEO}}$ is the total number of LEO satellites.

2.1.2. Geosynchronous and Geostationary Earth Orbit Satellites

Different from MEO satellites, inclined geosynchronous orbit (IGSO) satellites, which sit fixed at the crossover point of a figure-eight shape (over the equator), are relatively static to Earth in the ECEF system [32]. Therefore, the observation probability $P_I$ of an IGSO satellite depends on both $\omega_{\phi_j}$ and $\omega_{\lambda_i}$, which can be calculated as follows:

$$P_I(\lambda_i, \phi_j) = \begin{cases} \frac{\kappa}{\omega_{\max}} & (\lambda_i, \phi_j) \in (\lambda_{\text{IGSO}}, \phi_{\text{IGSO}}) \\ 0 & (\lambda_i, \phi_j) \notin (\lambda_{\text{IGSO}}, \phi_{\text{IGSO}}) \end{cases}$$

(6)

where $\omega_{\max} = \max\{\omega_{\lambda_i}, \omega_{\phi_j}\}$ is the maximum of $\omega_{\phi_j}$ and $\omega_{\lambda_i}$ [30], and $(\lambda_{\text{IGSO}}, \phi_{\text{IGSO}})$ is the ground track of an IGSO satellite. The calculation of IGSO satellite trajectories is described in [30].

The observation probabilities of the IGSO satellites for all grids satisfy:

$$\sum_{(\lambda_i, \phi_j) \in (\lambda_{\text{IGSO}}, \phi_{\text{IGSO}})} P_I(\lambda_i, \phi_j) = n_{\text{IGSO}}$$

(7)

where $n_{\text{IGSO}}$ is the total number of IGSO satellites.

Equation (6) can also be used to express the observation probability of a quazi-zenith orbit (QZO) satellite whose trajectory is an asymmetric eight [33]. Likewise, the total number of QZO satellites $n_{\text{QZO}}$ satisfies:

$$\sum_{(\lambda_i, \phi_j) \in (\lambda_{\text{QZO}}, \phi_{\text{QZO}})} P_Q(\lambda_i, \phi_j) = n_{\text{QZO}}$$

(8)
Geostationary Earth orbit (GEO) satellites are also relatively static to the Earth in the ECEF system. Therefore, the GEO satellite observation probability \( P_G \) can be expressed as:

\[
P_G(\lambda_i, \phi_j) = \begin{cases} 
1 & (\lambda_i, \phi_j) \in (\lambda_{\text{GEO}}, \phi_{\text{GEO}}) \\
0 & (\lambda_i, \phi_j) \notin (\lambda_{\text{GEO}}, \phi_{\text{GEO}})
\end{cases}
\]  

(9)

where \((\lambda_{\text{GEO}}, \phi_{\text{GEO}})\) is the designated position. For instance, three BDS-3 GEO (BDS-3G) are located at 80°E, 110.5°E, and 140°E, respectively [9].

2.2. Satellite Visibility and DOPs

The original pseudo-range observation equations can be generally described as follows [34]:

\[
v = Ax + e_n dt_r + t
\]

(10)

where \(v\) denotes the residuals, \(A\) is the design matrix for the coordinate unknowns \(x\); \(dt_r\) is the receiver clock error, while \(e_n\) is the \(n\)-column vector with all elements being 1, and \(t\) is the observed minus computed (OMC) difference, where the observed part is the pseudo-range observations and where the calculated part is the geometric distance between the satellite and the receiver [35].

Applying the least-squares (LS) criterion to solve Equation (10) yields the coefficient matrix \(G\) of the normal equations as:

\[
G = H^T H = \begin{bmatrix} 
\sum_{s=1}^{n} \left( \frac{\Delta x_s^2}{\rho_0^2} \right)^2 & \sum_{s=1}^{n} \frac{\Delta x_s \Delta y_s}{\rho_0^2} & \sum_{s=1}^{n} \frac{\Delta x_s \Delta z_s}{\rho_0^2} \\
\sum_{s=1}^{n} \frac{\Delta y_s \Delta x_s}{\rho_0^2} & \sum_{s=1}^{n} \left( \frac{\Delta y_s^2}{\rho_0^2} \right)^2 & \sum_{s=1}^{n} \frac{\Delta y_s \Delta z_s}{\rho_0^2} \\
\sum_{s=1}^{n} \frac{\Delta z_s \Delta x_s}{\rho_0^2} & \sum_{s=1}^{n} \frac{\Delta z_s \Delta y_s}{\rho_0^2} & \sum_{s=1}^{n} \left( \frac{\Delta z_s^2}{\rho_0^2} \right)^2 
\end{bmatrix}
\]

(11)

where \(n\) is the number of visible satellites above the cutoff elevation angle (CEA); \(H = \begin{bmatrix} A & e_n \end{bmatrix}\) is the geometric observation matrix of \(n \times 4\); \(\rho_0\) is the distance between the station’s approximate coordinates \((X_0, Y_0, Z_0)\) and the satellite coordinates \((x^s, y^s, z^s)\), and \(\Delta x^s = X_0 - x^s, \Delta y^s = Y_0 - y^s, \Delta z^s = Z_0 - z^s\).

By dividing the whole sky into 1° × 1° grids, each element of the \(G\) can be approximated through the following equation:

\[
\sum_{s=1}^{n} \left( \frac{\Delta x_s^2}{\rho_0^2} \right)^2 = \sum_{\lambda_i=1}^{90} \sum_{\phi_i=1}^{90} \frac{90}{ \rho_0^2} P_M(\lambda_i, \phi_i) \left( \frac{\Delta x_i^2}{\rho_0^2} \right)^2 + \sum_{\lambda_i=1}^{90} \sum_{\phi_i=1}^{90} \frac{90}{ \rho_0^2} P_L(\lambda_i, \phi_i) \left( \frac{\Delta y_i^2}{\rho_0^2} \right)^2 + \sum_{\lambda_i=1}^{90} \sum_{\phi_i=1}^{90} \frac{90}{ \rho_0^2} P_G(\lambda_i, \phi_i) \left( \frac{\Delta z_i^2}{\rho_0^2} \right)^2
\]

(12)

and the number of visible satellites \(n\) can be estimated as:

\[
n = \sum_{\lambda_i=1}^{90} \sum_{\phi_i=1}^{90} P_M(\lambda_i, \phi_i) + \sum_{\lambda_i=1}^{90} \sum_{\phi_i=1}^{90} P_L(\lambda_i, \phi_i) + \sum_{\lambda_i=1}^{90} \sum_{\phi_i=1}^{90} P_G(\lambda_i, \phi_i)
\]

(13)

The covariance matrix \(Q\) can be calculated as follows:

\[
Q = G^{-1}
\]

(14)

According to the variance and covariance propagation law, \(Q\) can be translated into \(Q_{\text{UENT}}\), which represents the covariance matrix expressed in the topocentric coordinate system [31]. Additionally, UENT means up (U), north (N), east (E), and receiver clock
offset. Thus, the geometric DOP (GDOP), position DOP (PDOP), horizontal DOP (HDOP), vertical DOP (VDOP), north DOP (NDOP), east DOP (EDOP), and time DOP (TDOP), by definition, can be calculated as Equation (15). The PDOP, which is composed of HOOP and VDOP, represents the satellite geometry accuracy in the 3D position \[19,20\]. The TDOP specifies the effect of the measurement error on the timing accuracy \[36\]. The lower the DOPs, the better the geometry, and the better the accuracy \[20\].

\[
\begin{align*}
GDOP &= \sqrt{\text{tr}(Q_{\text{UENT}})} \\
PDOP &= \sqrt{Q_{\text{UENT}}(1,1)} + Q_{\text{UENT}}(2,2) + Q_{\text{UENT}}(3,3) \\
HDOP &= \sqrt{Q_{\text{UENT}}(2,2)} + Q_{\text{UENT}}(3,3) \\
VDOP &= \sqrt{Q_{\text{UENT}}(1,1)} \\
EDOP &= \sqrt{Q_{\text{UENT}}(2,2)} \\
NDOP &= \sqrt{Q_{\text{UENT}}(3,3)} \\
TDOP &= \sqrt{Q_{\text{UENT}}(4,4)}
\end{align*}
\]

3. Results

3.1. Four-GNSS

Detailed characteristics of the four-GNSS constellations are given in Table 1. According to the satellite observation probability estimation methodology, we derived the $P_M(\lambda, \phi)$ of the four-GNSS MEO satellites were calculated. The results are presented in Figure 1. Moreover, 12 Galileo 2nd Generation satellites will join the existing constellation \[13,14\]. In the future, there will be 36 Galileo satellites in space to provide global services. Hence, the results of the full Galileo constellation are also shown in Table 1 and Figure 1. The satellite observation probability of BDS-3M is similar to that of the 24-satellite Galileo constellation and is less than that of the GPS and the 36-satellite Galileo constellation because there are fewer MEO satellites in BDS-3. With the largest orbit inclination, GLONASS satellites cover a wider range of latitudes, which disperses the probability of latitudinal distribution and results in a minimum observation probability compared to the other systems. Based on the observation probability, the satellite visibility and the DOPs of four-GNSS and their next-generation constellations are estimated and analyzed in the following paragraph.

![Figure 1. Distribution the observation probabilities of the GPS (32-satellite), BDS-3 MEO (BDS-3M 24-satellite), Galileo (24-satellite, and 36-satellite), and GLONASS (24-satellite) satellites.](image-url)
Table 1. Constellation parameters of four-GNSS and κ of the observation probabilities of MEO satellites.

| System            | GPS | Galileo | GLONASS | -BDS-3 |
|-------------------|-----|---------|---------|--------|
| Orbit Type        | MEO | MEO     | MEO     | GEO    | IGSO   | MEO    |
| Satellite Number  | 32  | 24 (36) | 24      | 3      | 3      | 24     |
| Angle of Inclination | 55° | 56°     | 64.8°   | 0°     | 55°    | 55°    |
| Altitude (km)     | 20,200 | 23,222 | 19,100  | 35,786 | 35,786 | 21,528 |
| Center of Longitude | -   | -       | -       | 80°E/110.5°E/140°E | 110.5°E | -      |
| κ (×10^{-4})      | 2.6730 | (2.5569) | 2.0026  | -      | 1.8574 |

BDS-3 adopts a heterogeneous constellation design and comprehensively completes deployment [9]. For future development, Yang et al. [10] provided several suggestions, one of which was to increase the inclination of IGSO satellites to improve the navigation services in the Arctic region for scientific research and transportation. Based on the observation probability of IGSO satellites \( P_I(\lambda_i, \phi_j) \), we derived the average elevation angle \( \overline{E}_I \) of the IGSO satellites through Equation (16):

\[
\overline{E}_I = \frac{\sum P_I(\lambda_i, \phi_j) \cdot E_{ij}}{\sum P_I(\lambda_i, \phi_j)}
\]  

(16)

where \( E_{ij} \) is the elevation angle of a satellite on the grid \((\lambda_i, \phi_j)\).

The \( \overline{E}_I \) of the IGSO constellations with 55°, 60°, 65°, 70°, and 75° inclinations are presented in Table 2. It can be seen that with the nominal constellation parameters of BDS-3I, the average elevation angle is 31.02 at high latitudes \((75° \leq |\beta| \leq 90°)\) in the Eastern Hemisphere. The improvement rate of the average elevation angle is approximately 7% when the inclination of the IGSO is increased by 5°. The average elevation angle reaches 40.06° when the inclination of 3 BDS-3I increases to 75°.

Table 2. Statistical results of the average elevation angles of IGSO satellites with different inclinations and their improvement rate compared those with a 55° IGSO inclinations.

| \(i_{orb}(°)\) | Area     | Ave. \(^1(°)\) | Imp. Rate \(^2\)(%) |
|----------------|----------|-----------------|---------------------|
| 55             | 31.02    | -               | -                   |
| 60             | 33.43    | 7.77            |                     |
| 65             | 35.75    | 15.25           |                     |
| 70             | 37.95    | 22.34           |                     |
| 75             | 40.06    | 29.14           |                     |

\(^1\) The “Ave.” represents the average. \(^2\) The “Imp. Rate” represents the improvement rate, which is defined as \( \frac{\text{Ave.}(\lambda_i, \phi_j)}{\text{Ave.}(\lambda_i, \phi_j)} \times 100\% \), where \(i_{orb} = 60°, 65°, 70°, 75°\).

To assess the performance of BDS-3 by adjusting the inclination of BDS-3I from 55° (BDS-3-nominal) to 75° (BDS-3-simulation), satellite visibility and GDOP were calculated. The results are shown in Figure 2 and Table 3. The number of visible BDS-3-nominal satellites ranges from 7 to 15 (average: 10.46), which is almost the same as that of the BDS-3-simulation (average: 10.49). Specifically, in the Asia-Pacific region, more than 12 satellites can be observed. The GDOP for both is less than 2.4. As the BDS-3I inclination increases, the GDOP decreases by approximately 3.8–8.0% (average: 6.9%) in the high-latitude region, while that in the high latitudes of the Eastern Hemisphere, the GDOP is 7.2% on average. It is clear that the BDS-3-simulation constellation can improve the geometric distribution of satellites in the Arctic region.
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| Area Ave. (°) | Imp. Rate (%) |
|---------------|---------------|
| 55° ≤ | ≤ 90° | 1800 E ≤ | B ≤ ≤ L | 31.02 | - | 60° | 33.43 | 7.77 |
| 65° | 35.75 | 15.25 |
| 70° | 37.95 | 22.34 |
| 75° | 40.06 | 29.14 |

1 The “Ave.” represents the average. 2 The “Imp. Rate” represents the improvement rate, which is defined as \( \frac{100 \times (\text{Ave.} - 55°)}{55°} \), where \( \text{orbi} \in \{75°, 70°, 65°, 60°\} \).

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Table 3. Statistical results of satellite visibility and GDOP for BDS-3-simulation, Galileo 2nd, 30-GLONASS, and the four-GNSS-NG, and its improvement rate compared to BDS-3-nominal, Galileo 1st, 24-GLONASS, and four-GNSS, respectively.

| System          | Satellite Visibility | Imp. Rate (%) | GDOP  | Imp. Rate (%) |
|-----------------|----------------------|---------------|-------|---------------|
| BDS-3-simulation| 10.49                | 0.6           | 2.52  | 2.1           |
| Galileo 2nd     | 12.80                | 50            | 2.26  | 18.4          |
| 30-GLONASS      | 10.59                | 28.2          | 2.45  | 10.1          |
| four-GNSS-NG    | 44.86                | 17.2          | 1.19  | 7.8           |

The first satellite of the Galileo 2nd generation is anticipated to launch before the end of 2024, and the full Galileo constellation will consist of 36 satellites [13,14,37]. Figure 3 shows the satellite visibility and GDOP of the 1st generation Galileo (Galileo 1st) and the full constellation (Galileo 2nd). With the number of total satellites increasing, the visible satellites of Galileo 2nd range from 11 to 14 (average: 12.80), which is about four more than that of the 1st generation (average: 8.53). Ranging from 2.02 to 2.78 (average: 2.26), the improvement rate of the Galileo 2nd GDOP is 18.4% on average. In general, the GDOP of the Galileo 2nd is smaller in mid–low latitude regions (range from 2.08 to 2.41) than it is at 75° \( \leq |B| \leq 90° \) latitude regions (range from 2.44 to 2.72).
Table 3. Statistical results of satellite visibility and GDOP for BDS-3-simulation, Galileo 2nd, 30-GLONASS, and the four-GNSS-NG, and its improvement rate compared to BDS-3-nominal, Galileo 1st, 24-GLONASS, and four-GNSS, respectively.

| System          | Ave. Satellite Visibility | Imp. Rate (%) | Ave. GDOP | Imp. Rate (%) |
|-----------------|---------------------------|---------------|-----------|---------------|
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To improve performance over Russia, GLONASS plans to add IGSO or high Earth orbit (HEO) satellites; however, orbit parameters are still under discussion [11,12]. In this study, we simulate six IGSO (GLONASS-I) satellite-enhancement constellations. Satellites equally operate in three orbits with a center longitude of 60\( ^{\circ} \)E, 90\( ^{\circ} \)E, and 120\( ^{\circ} \)E, respectively, to ensure the availability of augmentation over the whole of Russia. The inclination of the orbital planes is 64.8\( ^{\circ} \), which is the same as that of the GLONASS MEO satellites. The satellite visibility of 24-GLONASS and 30-GLONASS as well as the GDOP are shown in Figure 4. It can be seen that 7–10 satellites of 24-GLONASS can be observed worldwide. Fewer satellites can be observed over mid-latitude regions (5\( ^{\circ} \leq |B| \leq 45\degree \)) if compared to visibility at other latitudes. Adding six GLONASS-I to 24-GLONASS increases the number of visible satellites by 1.7–6 (average: 3.46) in the Eastern Hemisphere. In Russia and its surrounding areas (20\( ^{\circ} \)E–170\( ^{\circ} \)W, 40\( ^{\circ} \)N–85\( ^{\circ} \)N), the improvement is from 1.8 to 4.33 (average: 3.08). The GDOP of 24-GLONASS is smaller at latitudes of 45–70\( ^{\circ} \) than it is at lower latitudes and at the north and south ends. For 30-GLONASS, the GDOP decreases by 15.7% on average in the Eastern Hemisphere and by 14.4% in (20\( ^{\circ} \)E–170\( ^{\circ} \)W, 40\( ^{\circ} \)N–85\( ^{\circ} \)N) regions.
The GPS modernization program includes 10 GPS III satellites and 22 GPS IIIF satellites. The previous generation orbit parameters are still adopted for the 32 MEO satellites [7,38]. The satellite visibility and GDOP of the GPS are plotted in Figure 5. More GPS satellites can be observed over low latitudes ($|B| \leq 15^\circ$) and high latitudes ($|B| \geq 60^\circ$), which is similar to the distribution of Galileo. Compared to BDS-3 and 30-GLONASS, the number of visible GPS and Galileo satellites is more globally balanced. However, although there are fewer satellites in the BDS-3 and 30-GLONASS constellations, they show better GDOP in the Asia-Pacific region and in the high latitudes of the Eastern Hemisphere, which are benefits of GEO and IGSO satellite-augmented MEO constellations.

![Figure 4](image_url) (a) visible satellites of 24-GLONASS; (b) visible satellites of 30-GLONASS; (c) GDOP of 24-GLONASS; (d) GDOP of 30-GLONASS.

![Figure 5](image_url) (a) visible satellites of GPS; (b) GDOP of GPS.
The satellite visibility and GDOP of the four-GNSS and four-GNSS-NG are illustrated in Figure 6. The number of visible four-GNSS satellites is 33–45 worldwide (average: 38.25). When the four-GNSS are upgraded, the average number visible satellites of the four-GNSS-NG will reach 44.86, which is an increase of 6-7 satellites compared to four-GNSS. With the help of the BDS-3I, BDS-3G, and GLONASS-I satellites, the Asia-Pacific region will become the hottest GNSS area in the world, and more than 45 satellites will be able to be observed. In contrast, the number of observed satellites in the North, Central, and South America regions will be fewer. However, at least 37 satellites will still be able to be observed. Overall, the combination positioning of the four-GNSS-NG can greatly enhance the availability of satellite navigation and can provide more observations for global users. A benefit of the satellite visibility increasing is that the four-GNSS-NG satellites exhibit a better geometrical structure, which is helpful for the significant decrease in the GDOP. The average GDOP of the four-GNSS-NG is 1.19, which is an improvement rate of 7.8% on average compared to that of four-GNSS (average: 1.29). Additionally, at high-latitude regions, there is a distinct GDOP increase of nearly 1.2, which is mainly caused by the lower elevation of the satellites observed and an increase in the station latitude.

![Figure 6. Satellite visibility and GDOP of four-GNSS: (a) visible satellites of four-GNSS; (b) visible satellites of four-GNSS-NG; (c) GDOP of four-GNSS; (d) GDOP of four-GNSS-NG.](image-url)
to 0.39) for 25°S–25°N, while for other areas, the accuracy in the north–south direction is lower than it is in the east–west direction.

Figure 6. Satellite visibility and GDOP of four-GNSS: (a) PDOP; (b) TDOP; (c) HDOP; (d) VDOP; (e) NDOP; (f) EDOP.

Figure 7. DOPs of four-GNSS-NG: (a) PDOP; (b) TDOP; (c) HDOP; (d) VDOP; (e) NDOP; (f) EDOP.

In summary, more visible four-GNSS-NG satellites can be observed on a global scale. This is helpful, as it strengthens the satellite geometry and contributes to rapid changes in the geometric distribution the satellites, which can effectively mitigate multipath effects and can shorten the convergence time in precise positioning.

3.2. LEO-Augmented Four-GNSS

Similar to four-GNSS constellations, the LEO constellation, serving as a navigation system, should satisfy satellite visibility as well as DOP, which is equally distributed as much as possible on a global scale [39]. In this paper, we simulate six LEO constellation schemes in terms of orbital planes and orbital inclinations to study the distribution of LEO
satellites. The detailed information of the six Schemes LEO constellations is presented in Table 4. Schemes 1 and 2 LEO constellations adopt polar orbits with altitudes of 1000 km and 600 km, respectively. Schemes 3–5 are designed with an inclined orbit. The altitude of Schemes 3–5 is 1000 km. The inclination angles for Schemes 3–5 are 65°, 60°, and 30°, respectively. For Scheme 6, we designed mixed-orbit LEO constellations and included both the polar orbit and the inclined orbit, and all of the satellites operate in orbit at an altitude of 1000 km.

Table 4. Orbital configurations of the designed LEO constellations.

| Scheme | Orbit Type | Angle of Inclination | Altitude (km) |
|--------|------------|----------------------|---------------|
| 1, 2   | Polar      | 90°                  | 1000          |
|        |            | 60°                  | 600           |
| 3, 4, 5| Inclined   | 65°                  | 1000          |
|        |            | 60°                  |               |
|        |            | 30°                  |               |
| 6      | Polar + Inclined | 90° + 65° + 30°     | 1000          |

According to the principle of GNSS, availability means that more than four LEO satellites above a specific CEA can be observed on a global scale, for the ground receiver needs at least four satellite signals to determine its position, which can be expressed as follows:

\[
\min \left( \sum P_L(\lambda_i, \phi_j) \right) \geq 4
\]  

(17)

According to Equation (17), the results of the minimum number of LEO constellations with global service ability for Schemes 1–5 were calculated, which are listed in Table 5. Because a lower altitude implies narrower coverage for LEO satellites, Schemes 1–3 need at least 126, 220, and 196 LEO satellites, respectively, to ensure global coverage. That is far more than the total number of GNSS satellites. The satellite visibility of LEO constellation Schemes 4 and 5, whose orbit inclinations are smaller, drops rapidly at high latitudes, which results in their coverage being \(|B| \leq 81^\circ\) and \(|B| \leq 49^\circ\), respectively, with 183 and 202 satellites.

Table 5. The minimum number of designed LEO constellations and their coverage areas.

| Scheme | Number | Coverage    | \(\kappa\) |
|--------|--------|-------------|------------|
| 1      | 126    | globe       | 0.0070     |
| 2      | 220    | globe       | 0.0133     |
| 3      | 196    | globe       | 0.0111     |
| 4      | 183    | \(|B| \leq 81^\circ\) | 0.0104     |
| 5      | 202    | \(|B| \leq 49^\circ\) | 0.0117     |

According to the number of satellites of each LEO constellation, the observation probabilities of the LEO satellites \(P_L(\lambda_i, \phi_j)\) for the five schemes are plotted in Figure 8. Due to the increasing number of satellites, the \(P_L(\lambda_i, \phi_j)\) is much larger than the \(P_M(\lambda_i, \phi_j)\) of the GNSS. The distribution of polar-orbiting LEO constellations (Schemes 1 and 2) is more even than that of inclined-orbiting LEO constellations at all latitudes. Because a satellite travels north–south over the Earth, and the angular velocity is only in this direction. Comparing to Schemes 3 and 4, the distribution of the Scheme 5 LEO satellites with an inclination angle of 30° is narrower, which results in higher observation probabilities.
The coverage of the five Schemes LEO constellations is shown in Figure 9. Obviously, for Schemes 1 and 2, the satellite visibility varies greatly with increasing latitude, from approximately 4 LEO satellites at low latitudes to more than 16 at high latitudes. Scheme 3 is the most abundant in terms of visible satellites in the middle latitude region, with the number of visible satellites being over 10; however, that value significantly decreases in high-altitude regions. With a lower orbit inclination, the number visible satellites for Scheme 5 LEO constellation are larger in the low-latitude regions (30°S–30°N), where more than 12 satellites are visible.

LEO constellations with different orbit parameters have great differences in satellite visibility. To satisfy the equally distributed LEO satellites as much as possible on a global scale, we designed mixed-orbit LEO constellations (LEO-mix), which are presented as Scheme 6. Each orbit of the LEO-mixed constellation contains 40 satellites. The satellite
visibility of the Scheme 6 LEO constellations ranges from 5 to 8 (average: 6.53) over all latitudes, which is shown in Figure 6 (red line).

Figure 10 presents the satellite visibility and GDOP of LEO-mix (Scheme 6) with the four-GNSS-NG, respectively, and the corresponding Figure 10b,d illustrate their improvement rate compared to the four-GNSS-NG. As shown in Figure 10a,c, LEO-mixed satellites can fill the coverage gap in the polar area, which is helpful for users at high latitudes ($|\beta| > 60^\circ$). With more visible LEO satellites in this region (average: 6.86), the average improvement rate of the four-GNSS-NG+LEO-mix reaches 14.7%. Likewise, in the mid–low latitude region of the Western Hemisphere, approximately five more satellites can be observed, and the improvement rate is 14.4% on average. In general, the average visible satellites of the four-GNSS-NG+LEO-mix is 50.97. Ranging from 0.95–1.25 (average: 1.12), the GDOP of the four-GNSS-NG+LEO-mix decreases by about 4.1–11.0% (average: 6.2%) compared to four-GNSS-NG, and at the high latitudes, that value is almost more than 9%.

### Figure 10. Satellite visibility and GDOP of the four-GNSS-NG+LEO-mix satellites and their improvement rate: (a) visible satellites of four-GNSS-NG+LEO-mixed; (b) visible satellites improvement rate of the four-GNSS-NG+LEO-mix compared to that of the four-GNSS-NG; (c) GDOP of the four-GNSS-NG+LEO-mix; (d) GDOP improvement rate of the four-GNSS-NG+LEO-mix compared to that of the four-GNSS-NG.

Overall, new LEO satellites will provide the better signal coverage at high latitudes, which are not well-covered at the present. This contributes to ensuring the efficiency of all kinds of scientific research and to the safety of transportation in the Arctic region.

### 3.3. RNSS + Four-GNSS

At present, three QZO satellites and one GEO satellite make up QZSS, and these satellites transmit signals to provide services [40]. Three QZSS satellites, which will be deployed in the future, include one QZO satellite and two GEO satellites, one of which has a small inclination angle and is called a quasi-geostationary Earth orbit (QGEO) satellite [41].
The 7-QZSS satellite constellation parameters are listed in Table 6. Their ground tracks are plotted in Figure 11a. For the NavIC (formerly known as IRNSS), seven satellites—4 in geosynchronous and 3 in geostationary orbits, are on-orbit operations [42,43]. In the future, five new visible satellites (NVS) will be added to the constellation, in which NVS-01 (also known as IRNSS-1J) will replace IRNSS-1G, while the other satellite (NVS-02-NVS-05) parameters are summarized in Table 6 [43]. The ground tracks of the 11-NavIC satellites are shown in Figure 11b.

Table 6. Constellation parameters of QZSS and NavIC.

| System | QZSS | NavIC |
|--------|------|-------|
| Orbit Type | GEO | QGEO | IGSO |
| Satellite Number | 2 | 1 | 8 |
| Angle of Inclination | 0° | >1° | 29° |
| Altitude (km) | 35,786 | 35,786 | 42° |
| Center of Longitude | 90°E/127.5°E | 185°E | 55°E/111.75°E |
| | 139°E/148°E | 34°E/83°E/131.5°E |

Figure 11. (a) ground tracks of 7-QZSS; (b) ground tracks of 11-NavIC.

The method discussed earlier was used to assess the QZSS satellite visibility. The results are presented in Figure 12a,b, and Table 7 (to simplify the calculation, the QGEO satellite is regarded as a GEO satellite). One can see that the QZSS service is roughly in the Asia-Pacific region. More than two satellites can be observed for 4-QZSS in (60°E–180°E, 60°S–60°N), while 7-QZSS exceeds four. Specifically, in Southeast Asia and in Northwestern Australia, five visible satellites can be guaranteed. However, QZSS satellites are rarely observed at low altitudes in the Western Hemisphere. Similar to the QZSS, there are almost no visible NavIC satellites in most areas of North and South America. For 7-NavIC, four or more visible satellites are present in (30°E–150°E, 60°S–60°N) while the number of 11-NavIC satellites reaches six. Specifically, with full 11-NavIC constellations, at least 10 satellites are always visible from the whole India as well as its surrounding areas. Generally, the visibility of 7-QZSS satellites (average: 5.57) increases by 0.9–3 (average: 2.17) in the areas of (60°E–180°E, 60°S–60°N) compared to 4-QZSS satellites, and the value for 11-NavIC satellites (average: 8.78) with 7-NavIC is 1.83–4 (average: 3.11) in the areas of (30°E–150°E, 60°S–60°N).
To evaluate the contribution of QZSS and NavIC for regional services, the estimated number of the four-GNSS-NG+7-QZSS and four-GNSS-NG+11-NavIC visible satellites as well as their combination GDOP positioning were calculated. As shown in Figure 13 and Table 7, with a 5° mask, there are more than 37 four-GNSS-NG+7-QZSS satellites (average: 50.94) in the Eastern Hemisphere. Particularly, in the area of (60°E–180°E, 60°S–60°N), that number increases to 50 or more. The maximal improvement rate of satellite visibility, compared to the four-GNSS-NG, reaches 15.7%, while the average is 7.6%. Adding 7-QZSS to the four-GNSS-NG reduces the GDOP by 18.0% on average, and that value ranges from 10.8% to 35% (average: 27%) in (60°E–180°E, 60°S–60°N). In general, the GDOP basically reduces to a value within 1.16, and the average is 0.95. For four-GNSS-NG+11-NavIC
combination positioning, the number visible satellites ranges from 43.93 to 65.00 (average: 53.80), with the exception of a small area in the extreme north India, more than 59 usable satellites are always visible over the entire Indian landmass. Ranging from 0.60 to 1.17, the GDOP of the four-GNSS-NG+11-NavIC is 0.86 on average in the Eastern Hemisphere, which is an improvement of 8.3–42.9% (average: 26.1%) compared to the four-GNSS-NG. Especially in India and Southeast Asia, the GDOP is less than 0.68, and the improvement rate is at least 34.0%.

According to the four-GNSS and two RNSSs development programs, Figure 14 presents the satellite visibility and DOPs of the four-GNSS-NG+7-QZSS+11-NavIC on a global scale. The statistical results are listed in Table 8. The number of visible satellites is from 37.51 to 71.58 (average: 51.24). More satellites can be observed in the low altitudes of the Eastern Hemisphere and less in the areas of North and South America. Comparing to the operating satellites of four-GNSS+4-QZSS+7-NavIC, the satellite visibility improvement rate is from 11.6% to 32.0% (average: 21.1%). With more visible satellites, the PDOP, ranging from 0.50 to 1.08 (average: 0.82), improves by 12.8% on average. As shown in the illustration, the PDOP generally increases in the areas of (60°E–130°E, 30°S–30°N) towards the east and west ends. The maximum PDOP is at around 30° latitude in the Western Hemisphere. The HDOP and VDOP range from 0.37 to 0.56 (average: 0.46) and 0.32 to 0.94.
(average: 0.67), respectively. Both of them are lower in the Asia-Pacific region. However, the HDOP is larger at $40^\circ \leq |B| \leq 50^\circ$, while VDOP is larger in (30°S–30°N) and in some high latitude areas. Figure 11e presents the ratio of NDOP/EDOP to explain the HDOP features. It can be seen that NDOP, which ranges from 0.26 to 0.44 (average: 0.34), is less than EDOP, which ranges from 0.27 to 0.38 (average: 0.34), in the areas of (30°S–30°N) and $75^\circ \leq |B| \leq 90^\circ$. Additionally, the east direction positioning accuracy is higher than that of the north in other areas. TDOP, which has same characteristics as PDOP, ranges from 0.22 to 0.64 (average: 0.44).

To conclude, adding 7-QZSS and 11-NavIC to the four-GNSS-NG creates a further increase of the number of visible satellites and a decrease of DOP values in the Asia-Pacific region, where the great majority of the world’s population and industrial activity are concentrated. This benefits high-precision positioning and navigation applications in urban environments, such as intelligent transportation and automated driving.

Figure 14. Satellite visibility and DOPs of the four-GNSS-NG+7-QZSS+11-NavIC: (a) visible satellites; (b) PDOP; (c) HDOP; (d) VDOP; (e) NDOP/EDOP; (f) TDOP.

Table 8. Statistical results of satellite visibility, PDOP, HDOP, VDOP, and TDOP of the four-GNSS-NG+7-QZSS+11-NavIC.
Table 8. Statistical results of satellite visibility, PDOP, HDOP, VDOP, and TDOP of the four-GNSS-NG+7-QZSS+11-NavIC.

| Orbit                    | Ave.  | Min. ¹ | Max.  |
|--------------------------|-------|--------|-------|
| Satellite visibility     | 51.24 | 37.51  | 71.58 |
| PDOP                     | 0.82  | 0.50   | 1.08  |
| HDOP                     | 0.46  | 0.38   | 0.56  |
| VDOP                     | 0.67  | 0.32   | 0.94  |
| NDOP                     | 0.34  | 0.26   | 0.44  |
| EDOP                     | 0.31  | 0.27   | 0.38  |
| TDOP                     | 0.44  | 0.22   | 0.64  |

¹ The “Min.” and “Max.” represent minimal and maximal value, respectively.

To conclude, adding 7-QZSS and 11-NavIC to the four-GNSS-NG creates a further increase of the number of visible satellites and a decrease of DOP values in the Asia-Pacific region, where the great majority of the world’s population and industrial activity are concentrated. This benefits high-precision positioning and navigation applications in urban environments, such as intelligent transportation and automated driving.

4. Discussion and Conclusions

With the wider application of GNSS technology in various fields, each navigation satellite system has created a modernization program to upgrade its features. To assess the performance of the next-generation GNSSs, RNSSs, and LEO augmentation constellations, we use the method by Wang et al., which does not require the actual ephemerides, which are not available before the constellation is deployed for full operation. Our analysis showed that the next-generation navigation satellite systems can significantly improve satellite availability and can strengthen geometric distribution. The increased satellite visibility can reduce the blind areas of GNSS services [17], and the better geometrical structure is helpful to reduce initialization periods [44], both of which contribute to high-precision GNSS applications, such as automated driving in urban environments and scientific research in the Arctic region.

This method can also be used to evaluate the performance of satellite-based augmentation system (SBAS) and other regional systems in development, such as the southern positioning augmentation network (SouthPAN) from Australia and New Zealand.

Of course, positioning accuracy is not only affected by satellite visibility and DOPs but also by other factors, such as satellite clock stability, which are needed for analysis when the next generation constellations are in full operation.

In summary, the results of this study will enrich the growing knowledge base of the new generation navigation satellite systems and will provide a basis for constellation selection and design.

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