Mechatronics and Automation Technology
J.-Y. Xu (Ed.)

doi:10.3233/ATDE231087

Simulation and Analysis of Multi-Signal Middle-Orbit Spacecraft Positioning Performance

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Abstract. To address the challenge of autonomous orbiting of space satellites under the increasing number of satellites in space,the Satellite Tool Kit (STK) is used to simulate and analyze the orbiting of medium-orbit satellites under Multi-Global Navigation Satellite System (Multi-GNSS) signals. The four global navigation systems and augmentation systems are modeled by STK. The satellite signals from the navigation systems are received by the middle earth orbit (MEO) satellite. The satellite signals from the navigation systems are received by the middle earth orbit (MEO) satellite receiver, and the number of visible stars, the Dilution of Precision (DOP) value, and the navigation and positioning accuracy are used as the evaluation indexes. The navigation systems are received by the middle earth orbit (MEO) satellite receiver, and the number of visible stars, the Dilution of Precision (DOP) value, and the navigation and positioning accuracy are used as the evaluation indexes to study the optimal positioning mode of the middle-orbit satellites in the case of multi-GNSS. concluded that under single-system positioning, the positioning accuracy of BEIDOU system is higher, up to 4 meters accuracy. Under dual-system positioning, the combined accuracy of BEIDOU system is higher, up to 4 meters accuracy. Under dual-system positioning, the combined accuracy of BEIDOU and the Global Positioning System (GPS) is higher, with an accuracy of about 3 meters.

Keywords. Simulation; Middle-orbit satellite; STK; Positioning performance.

1. Introduction

In recent years, with the increasing number of satellites, the orbiting of a huge number of satellites has become a problem that needs to be solved urgently. The original orbiting mode based on ground station has become oversaturated in front of huge number of satellites. Star-based satellite orbiting based on global navigation satellite system (GNSS) satellite receivers has become a new research direction[1] . The use of star-based GNSS receivers for satellite-based positioning can effectively alleviate the predicament of insufficient ground station receiving signal capacity. At present, the main research focuses on the satellite-based GNSS orbiting in high orbit and low orbit. Based on the global positioning system (GPS) satellites, low earth orbit (LEO)

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satellites can achieve centimeter-level accuracy after the fact precision orbiting.[2][3] The accuracy of real-time orbiting using single BeiDou data in literature [4] also reaches 3m, which is comparable to the accuracy of orbiting using GPS real-time data. The orbiting method using pseudo-distance plus clock difference modeling correction now achieves decimeter-level orbiting accuracy.[5] For high orbit localization, there are now also some methods to locate the high orbit. For high orbit positioning, there are also various aspects of algorithm research, in terms of accuracy, the literature [6] in the satellite receiver sensitivity adjusted to -185dbW when the high earth orbit (HEO) can achieve meter-level positioning accuracy. However, there are not many studies on GNSS positioning of mid-orbit satellites nowadays. Literature [7] studied the orbiting accuracy of middle earth orbit (MEO) in single Beidou navigation satellite system (BDS) mode, which is about 50 m. However, it did not study the orbiting accuracy of satellites under other conditions, such as multi-system joint orbiting.

This paper focuses on the autonomous orbiting requirements of mid-orbit spacecraft. The four major global satellite navigation systems and augmentation systems are modeled by the satellite tool kit (STK) software. We study the dilution of precision (DOP) values, the number of visible stars and the navigation accuracy of MEO satellites under various GNSS single and dual system fusion scenarios. In this way, the optimal orbiting mode of MEO satellites is sought. In order to provide reference for the subsequent research on MEO autonomous orbiting.[8] The following is a reference for the subsequent research on MEO autonomous orbiting.

2. Navigation Accuracy and Adaptability Rating Factors Analysis

2.1. Visibility

Visibility refers to the number of satellites that the user can observe at the same time, since at least 4 satellites need to be located simultaneously for the user to be able to locate the position[9] The visibility refers to the number of satellites the user can observe at the same time. To a certain extent, the more satellites that can be observed, the more accurate the positioning will be. By analogy, when positioning a spacecraft with GNSS, 4 satellites need to be observed at the same time, and the number of visible satellites can be used as a measure of the positioning performance of the GNSS or combination in positioning the spacecraft.[10] The number of visible stars can be used as an indicator of the performance of the GNSS or combination in positioning the spacecraft.

2.2. DOP

Precision factor is in the measurement of multiple points to the same point distance and thus into the positioning method, there are a variety of reasons will have an impact on its positioning accuracy, in order to quantify the error so use the precision factor to express the degree of impact on the accuracy of[11] . Divided into: Geometric Dilution of Precision (GDOP), Horizontal Dilution of Precision (HDOP), Vertical Dilution of Precision (VDOP), Time Dilution of Precision (VDOP)[12][13].

Let the coordinates of the known points be $\left(x_i, y_i, z_i\right), i = 1,2,3\cdots$,the point to be determined P is $\left(x, y, z\right)$, according to the distance formula can be obtained from the points to the point to be determined the distance r is

$$f\left(x, y, z\right) = r = \sqrt{\left(x_i - x\right)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{1}$$

Where $f\left(x, y, z\right)$ is the expression of the function of the distance r

The true position of the $P(x, y, z)$ is

$$x = x' + \Delta x \tag{2}$$

$$y = y' + \Delta y \tag{3}$$

$$z = z' + \Delta z \tag{4}$$

Where: $P'(x', y', z')$ is the approximate position of the point to be determined by the algorithm; Δx , Δy , Δz are the coordinate changes between the real position and the approximate position;

Thus the distance $f\left(x, y, z\right)$ can be expressed as

$$f\left(x, y, z\right) = f(x' + \Delta x, y' + \Delta y, z' + \Delta z) \tag{5}$$

The Taylor expansion at P' is given by

$$f\left(x, y, z\right) = f(x', y', z') + \left.\frac{\partial f}{\partial x}\right|_{p'} \Delta x + \left.\frac{\partial f}{\partial y}\right|_{p'} \Delta y + \left.\frac{\partial f}{\partial z}\right|_{p'} \Delta z \tag{6}$$

So the partial derivative at P' is:

$$\left.\frac{\partial f}{\partial x}\right|_{p'} = \frac{-(x_i - x')}{\sqrt{(x_i - x')^2 + (y_i - y')^2 + (z_i - z')^2}} = \frac{-(x_i - x')}{r_i'} \tag{7}$$

Where r_i' is the estimated distance from the known point to the point to be determined;

Let $\frac{-(x_i - x')}{r_i'} = a_{xi}$, and similarly define a_{yi} , a_{zi} , and then r_i to be

$$r_i = r_i' - a_{xi}\Delta x - a_{yi}\Delta y - a_{zi}\Delta z \tag{8}$$

Given $\Delta r_i = r_i' - r_i$, Δr_i can be expressed as

$$\Delta r_i = a_{xi}\Delta x + a_{yi}\Delta y + a_{zi}\Delta z \tag{9}$$

In the case where there are more than 4 known points, the system of simultaneous equations is

$$\begin{cases} \Delta r_1 = a_{x1}\Delta x + a_{y1}\Delta y + a_{z1}\Delta z \\ \Delta r_2 = a_{x2}\Delta x + a_{y2}\Delta y + a_{z2}\Delta z \\ \Delta r_3 = a_{x3}\Delta x + a_{y3}\Delta y + a_{z3}\Delta z \\ \cdots \\ \Delta r_n = a_{xn}\Delta x + a_{yn}\Delta y + a_{zn}\Delta z \end{cases} \tag{10}$$

Abbreviate Equation (10) as

$$\Delta r = H \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \tag{11}$$

where H is ; $\begin{bmatrix} a_{x1} & a_{y1} & a_{z1} \\ a_{x2} & a_{y2} & a_{z2} \\ a_{x3} & a_{y3} & a_{z3} \\ \cdots & & \\ a_{xn} & a_{yn} & a_{zn} \end{bmatrix}$ Δr is $\begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \cdots \\ \Delta r_n \end{bmatrix}$

let $\Delta A = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix}$

transforms to

$$\Delta A = (H^T H)^{-1} H^T \Delta r \tag{12}$$

change Δ into δ

$$\delta A = (H^T H)^{-1} H^T \delta r \tag{13}$$

Since the δA covariance is

$$cov(\delta A) = E(\delta A \ \delta A^T) \tag{14}$$

Bringing in Equation (13) as

$$cov(\delta A) = (H^T H)^{-1} H^T E(\delta r \delta r^T) H (H^T H)^{-T} \tag{15}$$

Since $E(\delta r \delta r^T)$ is the covariance, which is distributed independently among the points, it can be expressed as

$$E(\delta r \delta r^T) = \sigma^2 E_n \tag{16}$$

where σ^2 is the variance of each point; E_n is the Nth order unit array

Substituting Equation (16) into Equation (15) as

$$cov(\delta A) = \sigma^2 (H^T H)^{-1} \tag{17}$$

Let the matrix G be

$$G = (H^T H)^{-1} = \begin{vmatrix} G_{xx} G_{xy} G_{xz} \\ G_{yx} G_{yy} G_{yz} \\ G_{zx} G_{zy} G_{zz} \end{vmatrix} \tag{18}$$

Bringing in Equation (17) as

$$cov(\delta A) = \sigma^2 \begin{vmatrix} G_{xx} G_{xy} G_{xz} \\ G_{yx} G_{yy} G_{yz} \\ G_{zx} G_{zy} G_{zz} \end{vmatrix} \tag{19}$$

Thus the geometric accuracy factor can be defined as

$$GDOP = \sqrt{G_{xx} + G_{yy} + G_{ZZ}} \tag{20}$$

The horizontal accuracy factor can be defined as

$$HDOP = \sqrt{G_{xx} + G_{yy}} \tag{21}$$

Vertical accuracy factor can be defined as

$$VDOP = \sqrt{G_{ZZ}} \tag{22}$$

3. Middle-orbit Spacecraft Navigation Performance Simulation Analysis

3.1. Construction of the Simulation Scenario

Satellite visibility, DOP values and navigation accuracy for mid-orbit spacecraft are analyzed in different scenarios by using STK.[14] . The satellite orbit parameters are shown in table 1. The orbital altitude is 10000km and the orbital inclination is 15°. The experiment starts at 00:00:00 on March 1, 2022 and ends at 00:00:00 on March 10, 2022 with a step size of 1 minute.

Table 1. Orbital parameters for mid-orbit spacecraft

Parameters	Parameter Value
Start Time	2022/3/1 0:00
Stop Time	2022/3/10 0:00
Step Size	1 minute
propagator	J4
Orbit Epoch	2022/3/1 0:00
Coordinate Type	Classical
Coordinate System	J2000
Apogee Altitude	10000km
Perigee Altitude	10000km
Inclination	15 deg
Argument of Perigee	0.0 deg
RAAN	0.0 deg
True Anomaly	0.0 deg

3.2. Visibility Analysis of Mid-orbit Spacecraft Positioning

The data obtained after simulation tests with STK software can be used to compare the visibility of BeiDou, GPS, GLONASS, Galileo satellite navigation system (Galileo), and various augmentation systems[15] to mid-orbit satellites.

3.2.1. Single-system Satellite Visibility Analysis

The visibility results for each system are shown in figure 1 and table 2.

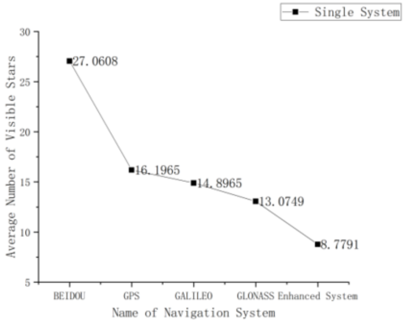


Figure 1. Average number of visible stars positioned by a single system on a mid-orbit spacecraft

Table 2. Average number of visible stars positioned by a single system on a mid-orbit spacecraft

Unit: pcs

Name of navigation system	Number of visible stars	Mean value
BEIDOU	12-41	27.0608
GPS	13-19	16.1965
GALILEO	11-19	14.8965
GLONASS	12-18	13.0749
Enhanced System	4-13	8.7791

Based on the above data, the following conclusions can be drawn:

(1) The maximum number of visible stars for BeiDou is 41, which is larger than the maximum number of visible stars for other GNSS.

(2) The difference between the GPS and GLONASS maxima and minima is 6, which is relatively stable.

Table 3. Average number of visible stars for dual-system localization of mid-orbit spacecraft

Navigation system combinations	Number of visible stars	Mean value
BEIDOU+GPS	26-58	43.2601
BEIDOU+GALILEO	25-58	42.01402
BEIDOU+GLONASS	24-56	40.1358
BEIDOU+ Enhanced System	16-53	35.8382
GPS+GALILEO	26-38	31.1524
GPS+GLONASS	25-36	29.2763
GPS+Enhanced System	18-31	24.9748
GLONASS+GALILEO	16-31	21.8523
GLONASS+ Enhanced System	23-35	28.0281
GALILEO+ Enhanced System	17-30	23.6682

3.2.2. Multi-system Satellite visibility Analysis

Based on the data in table 3, the following conclusions can be drawn:

(1) The average number of visible stars in the combination of BeiDou satellite navigation and GPS for the positioning of mid-orbit spacecraft is 43.26, which is the largest in the combination, indicating that the combination of BeiDou and GPS is optimal in the positioning of mid-orbit spacecraft.

(2) BeiDou satellite navigation has a significantly higher number of visible stars when combined with other GNSS to localize mid-orbit spacecraft.

In summary, it can be concluded that the combination of BeiDou satellite navigation and GPS can receive the most signals, indicating that BeiDou can play a good role in enhancing the positioning accuracy.

3.3. Analysis of DOP Values for Mid-orbit Spacecraft Positioning

The data obtained after simulation tests with the STK software can be compared with the DOP values of BeiDou, GPS, GLONASS, Galileo, and augmentation systems for the positioning of mid-orbit satellites.

Table 4. DOP values for single-system localization of mid-orbit spacecraft

Name of navigation system	GDOP	PDOP
BEIDOU	0.618-1.29	0.573-1.208
GPS	0.817-1.329	0.770-1.222
GALILEO	0.807-1.368	0.764-1.282
GLONASS	0.781-1.405	0.742-1.317
Enhanced System	1.291-640.682	1.239-640.668

3.3.1. Analysis of Single System DOP Values

An analysis based on the data in table 4 can be concluded:

(1) The positioning accuracy of the augmentation system slips severely when positioning mid-orbit spacecraft, and accurate positioning information is essentially unavailable.

(2) The difference between the minimum and maximum value of GDOP value of GPS is minimum 0.512 in GNSS, i.e., GPS has minimum GDOP value.

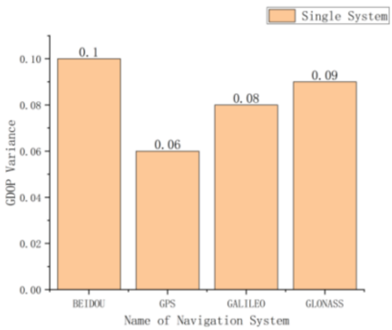


Figure 2. Comparison of GDOP variance for single-system localization of mid-orbit spacecraft

Based on the data in figure 2 it can be seen that the GDOP variance of GNSS is compared to show that GPS has the smallest GDOP variance, indicating that GPS has the highest stability.

In summary, GPS has the best localization performance in locating mid-orbit spacecraft, and the augmentation system has the worst localization performance.

Table 5. DOP values for dual-system localization of mid-orbit spacecraft

Navigation system combinations	GDOP	PDOP
BEIDOU+GPS	0.500-0.816	0.463-0.766
BEIDOU+GALILEO	0.498-0.849	0.460-0.790
BEIDOU+GLONASS	0.488-0.904	0.456-0.851
BEIDOU+ Enhanced System	0.544-1.145	0.505-1.071
GPS+GALILEO	0.559-0.889	0.528-0.832
GPS+GLONASS	0.572-0.872	0.544-0.814
GPS+Augmentation	0.639-1.143	0.603-1.057
GLONASS+GALILEO	0.620-1.194	0.586-1.117
GLONASS+ Enhanced System	0.573-0.931	0.541-0.873
GALILEO+ Enhanced System	0.675-1.114	0.636-1.031

3.3.2. Dual System DOP Value Analysis

An analysis based on the data in table 5 leads to the following conclusions:

(1) The difference between the minimum and maximum value of GDOP for the combination of GPS and GLONASS is 0.3, i.e., the minimum value of GDOP for the combination of GPS and GLONASS.

(2) The variance of the GDOP values for each combination was compared.

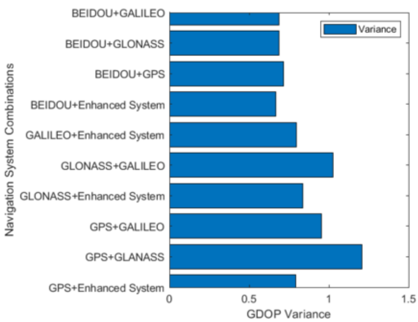


Figure 3. Comparison of GDOP variance for dual system localization of mid-orbit spacecraft

According to figure 3 it can be seen that the combined GPS and GLONASS and the combined GPS and Galileo GDOP have the smallest tied variance of 0.03, indicating that these two combinations have the highest stability.

3.4. Positioning and Navigation Accuracy Analysis for Mid-orbit Spacecraft

It is more intuitive to measure the accuracy of positioning by navigation accuracy when positioning a middle-orbit spacecraft, and the single and dual systems will be compared to determine which single and dual systems are more suitable for middle-orbit spacecraft positioning[16].

Table 6. Single-system positioning and navigation accuracy range for mid-orbit spacecraft

Unit: m

Name of navigation system	Navigation accuracy/m
BEIDOU	2.282-3.337
GPS	3.162-3.676
GALILEO	3.252-3.660
GLONASS	3.571-4.196
Enhanced System	5.155-20.350

3.4.1. Single System Navigation Accuracy Analysis

This can be derived from the data in table 6:

(1) The navigation accuracy values of BeiDou satellite navigation system are significantly lower than other satellite navigation systems, indicating that BeiDou satellite navigation system has high navigation accuracy.

(2) The navigation accuracy of the augmentation system is very low, indicating that the augmentation system is not suitable for localizing mid-orbit spacecraft.

In summary, the Beidou satellite navigation system has high positioning accuracy and is suitable for the positioning of spacecraft in medium orbit.

Table 7. Dual-system positioning and navigation accuracy range for medium-orbiting spacecraft

Unit: m

Navigation system combinations	Navigation accuracy/m
BEIDOU+GPS	1.810234-2.409936
BEIDOU+GALILEO	1.828394-2.38589
BEIDOU+GLONASS	1.871119-2.587224
BEIDOU+ Enhanced System	1.993945-2.794439
GPS+GALILEO	2.253414-2.543646
GPS+GLONASS	2.407537-2.701905
GPS+Augmentation	2.455566-2.927996
GLONASS+GALILEO	2.604998-3.204298
GLONASS+ Enhanced System	2.426501-2.734902
GALILEO+ Enhanced System	2.500174-3.018583

3.4.2. Dual System Navigation Accuracy Analysis

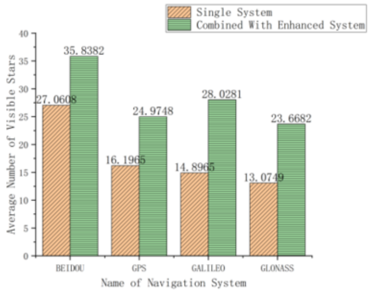
Based on the data in table 7, the following conclusions can be drawn:

(1) The navigation accuracies of the various combinations in localizing the mid-orbit spacecraft are not very different.

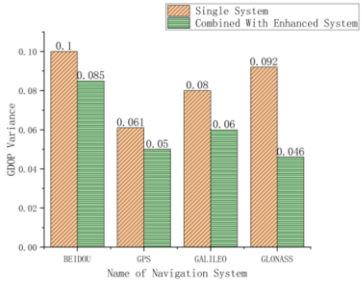
(2) Based on the images it can be seen that BEIDOU has better stability when combined with GPS.

3.5. Performance Analysis of Augmentation Systems for Single-system Mid-orbit Spacecraft Localization Enhancement

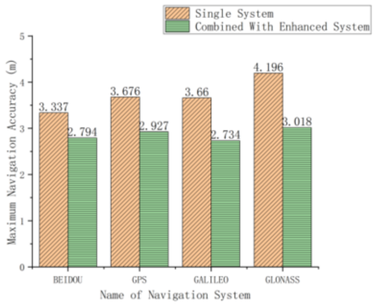
The single system and the augmented system are fused to locate the mid-orbit spacecraft and compared and analyzed based on the average number of visible stars, the variance value of the GDOP, and the maximum value of the localization accuracy, to derive the augmented system's augmentation performance to which single system is the best. As shown in figure 4:



(a) Comparison of the number of visible stars before and after enhancement of the positioning of a single-system mid-orbit spacecraft by the augmentation system



(b) Contrast of GDOP variance before and after augmentation of the augmented system to a single-system mid-orbit spacecraft positioning augmentation



(c) Comparison of maximum navigation accuracy before and after augmentation of the augmentation system to a single-system mid-orbit spacecraft positioning enhancement

Figure 4. Comparison of the maximum navigation accuracy before and after augmentation of the augmentation system to single system mid-orbit spacecraft positioning augmentation

Analysis based on the above comparative charts leads to the following conclusions

(1) Based on the increase in the number of visible stars, Galileo shows the largest increase, with more stars per star position visible to the mid-orbiting spacecraft when Galileo's constellation is fused with the augmentation system during the positioning of the mid-orbiting spacecraft.

(2) In the analysis of GDOP variance and navigation accuracy, the enhancement effect of Galileo is not as obvious as the enhancement effect of GLONASS. The reason may be that although Galileo has a large number of visible satellites, the satellite signals at the time of positioning are poorer due to the location of the navigation satellites.[17] The reason is that although Galileo has more visible stars, the signal received by the receiver is poorer due to the location of the navigation satellites, so the enhancement effect is not as good as that of GLONASS.[18] So although Galileo receives more satellites, the enhancement effect is not as good as GLONASS.

Combining the above conclusions, it can be concluded that the augmentation system has the best performance for GLONASS single system augmentation when it is fused with GLONASS for positioning. The enhancement effect of the augmentation system on Galileo should be equally obvious if the problem of navigation satellite transmission signal power is improved.

4. Summary

A series of comparative analyses of the positioning effectiveness of each GNSS single system with various two-system combinations for mid-orbiting spacecraft were conducted.

Mainly using the number of visible stars, DOP value and navigation accuracy as the measuring factors, which single system or which combination is more suitable for the localization of mid-orbit spacecraft in single and dual systems for the localization of high-orbit spacecraft, respectively, is obtained. The conclusions are summarized based on the above findings.

(1) When a single system is used for the positioning of spacecraft in medium orbit, the positioning performance of the Beidou satellite navigation system is somewhat better.

(2) The highest number of visible stars of the BeiDou satellite navigation system when a single system is used to locate medium-orbiting spacecraft indicates that the structure of the BeiDou navigation satellite constellation is suitable for locating medium-orbiting spacecraft and that there is a great prospect for development in locating medium-orbiting spacecraft.[19] The number of visible stars is the highest in the single-system positioning of medium-orbit spacecraft.

(3) The augmentation system is not conducive to the positioning of medium-orbiting spacecraft because of its high-orbiting satellites and the distribution of satellite constellations.

(4) The combination of BeiDou and GPS has the highest number of visible stars when positioning a medium-orbiting spacecraft in a dual-system, which, combined with the higher stability of the combination of GPS and GLONASS and the combination of GPS and Galileo, leads to the conclusion that the accuracy of a spacecraft combined with GPS will be higher than that of the other types of combinations when positioning a medium-orbiting spacecraft[20] .

The impact of using different optimization algorithms on orbiting accuracy can be further considered in the future on the basis of multi-satellite navigation system signals.

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