# GEO Precise Orbit Determination Based on GPS Single-Frequency C1/L1 Signal Spillover: Postprint

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## Abstract

With the increasing number of space activities, the use of GNSS receivers onboard high-orbit spacecraft to provide navigation services has emerged as a new research frontier. Using the Geostationary Earth Orbit (GEO) satellite TTS-2 as a case study, this work analyzes the characteristics of TTS-2' s onboard GPS single-frequency C1/L1 measurement data and noise properties. GEO onboard receivers can acquire both GPS main-lobe and side-lobe signals that are not obstructed by the Earth. The C1/L1 noise distribution exhibits a relatively large range and demonstrates a certain correlation with elevation angle. An orbit determination method based on a priori constraints on dynamic parameter errors is employed, with experiments conducted using different strategies for constraining dynamic parameters. The experimental results indicate that the orbit overlap consistency accuracy for GEO satellites utilizing onboard GPS C1/L1 data can achieve meter-level or even sub-meter-level precision. Under conditions where both the motion state and solar radiation pressure parameters are constrained, the three-dimensional RMS errors of orbit overlap for orbit determination arcs of 36 h and 72 h are both less than 0.65 m. When only the solar radiation pressure parameters are constrained, the three-dimensional RMS error of orbit overlap for a 72 h arc length is 1.0 m, while for a 36 h arc length it is less than 1.5 m. By adopting the orbit determination method with a priori dynamic parameter error constraints and appropriately setting the dynamic parameter errors, superior orbit solutions can be obtained.

# Full Text

## Preamble

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### GEO Precise Orbit Determination Based on GPS Single-Frequency C1/L1 Leakage Signals

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## Abstract

With the increasing number of space activities, high-orbit spacecraft equipped with GNSS receivers for navigation services has become a new research focus. Taking the geosynchronous orbit satellite TTS-2 as an example, this paper analyzes the onboard GPS single-frequency C1/L1 measurement data and its noise characteristics. GEO onboard receivers can acquire both the uncovered main-lobe signals and side-lobe signals from GPS satellites. The C1/L1 noise exhibits a large distribution range and shows a certain correlation with elevation angle. Using an orbit determination method with prior dynamic parameter error constraints, experiments were conducted with different dynamic parameter constraint strategies. The results demonstrate that the orbit overlap consistency of GEO satellite orbit determination using onboard GPS C1/L1 data can achieve meter-level or even sub-meter-level precision. When both the satellite motion state and solar radiation pressure parameters are constrained, the three-dimensional RMS errors for both 36-hour and 72-hour arc orbit determination are less than 0.65 m. When only solar radiation pressure parameters are constrained, the three-dimensional RMS error is 1.0 m for 72-hour arc orbit determination and less than 1.5 m for 36-hour arc orbit determination. By employing the prior dynamic parameter error constrained orbit determination method and setting reasonable dynamic parameter errors, an optimal orbit solution can be obtained.

**Keywords:** Orbit determination; GEO; Prior error constraint; Leakage signals

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## 1 Introduction

With the rapid development of Global Navigation Satellite Systems (GNSS), GNSS has gradually become an important means for air-space-ground users to obtain positioning services. Most spacecraft carry GNSS receivers to provide real-time position tracking or post-processed high-precision orbit support for their missions. However, domestic researchers have primarily focused on precise orbit determination for low-orbit spacecraft using onboard GPS or Multi-GNSS, such as Haiyang-2A [1], Ziyuan-3 [2,3], Fengyun-3 [4,5], and Tianping-1 [6] satellites. In recent years, with the increasing number of high-orbit satellite missions such as the Gaofen series and Fengyun series (Fengyun-4), as well as deep space exploration missions, using GNSS for navigation and positioning services on spacecraft above GNSS constellations has become a research hotspot. Employing GNSS for autonomous navigation on high-orbit spacecraft can not only effectively save ground TT&C resources but also improve orbit determination accuracy and spacecraft operational capabilities.

Since the late 20th century, Europe and the United States have pioneered on-orbit signal testing of GPS receivers on high-orbit spacecraft [7], and further achieved real-time navigation and orbit determination in the early 21st century [8-10]. Domestic research on high-orbit GNSS on-orbit testing started later. In 2014, the Chang' E-5 Test Vehicle (CE-5T), equipped with a GNSS receiver, collected GNSS signals at distances of (1-6)\$×10^{4}\$ km from Earth' s center, achieving navigation accuracy at the hundred-meter level [11,12]. In 2017, the No.2 Telecommunication Technology Test Satellite (TTS-2), equipped with a GNSS receiver, achieved real-time autonomous navigation with position accuracy better than 30 m using only pseudorange measurements and dynamic filtering [13,14]. Domestic researchers processed TTS-2 onboard GPS data using overlapping arc comparison analysis, obtaining three-dimensional RMS errors close to 2 m [15,16]. Wang et al. [13] comprehensively summarized the characteristics and orbit determination technologies of high-orbit GNSS and their development history, elaborating on the development direction of high-orbit GNSS applications.

For GEO satellite onboard GNSS receivers, the geometric distribution of visible GPS satellites is poor, the received signal power is low, and the space environment is harsh [13]. Based on this, this paper conducts research on precise orbit determination using TTS-2 onboard GPS data. First, the actual observation conditions of GEO onboard GPS receivers are introduced, and the data noise and Dilution of Precision (DOP) are analyzed. Then, the measurement equations and error corrections for GEO onboard single-frequency C1/L1 data are presented. Finally, considering the characteristics of GEO onboard GPS data, an orbit determination method with prior dynamic parameter error constraints is adopted to design experiments and evaluate orbit overlap consistency under different dynamic parameter constraint strategies. The research content of this paper provides important reference value for high-precision orbit determination of high-orbit spacecraft based on onboard GNSS.

## 2.1 GPS Leakage Signal Measurement Data

TTS-2 is a GEO satellite equipped with a GPS receiver for real-time navigation services. The GPS navigation antenna points toward Earth with a beam angle of approximately 42.6° [17]. Since TTS-2 operates at an altitude above the GPS constellation, the received GPS signals mainly consist of uncovered main-lobe signals and side-lobe signals—referred to as leakage signals. The visibility of GPS satellites from TTS-2 is shown in [Figure 1: see original paper]. The TTS-2 onboard GPS observation data collected for this study spans from DOY 100 16:00 to DOY 108 16:00 in 2018. The TTS-2 onboard GPS observations are C1/L1 single-frequency data with a sampling interval of 2 s.

The nadir visibility map of GPS constellation from TTS-2 is shown in [Figure 2: see original paper] (satellite-fixed coordinate system: x-axis points in the flight direction, z-axis points toward Earth's center, y-axis completes the right-handed system). The maximum elevation angle of received GPS signals is approximately -51°. Since the minimum elevation angle for receiving GPS signals is about -83°, the central portion of Figure 2 appears blank. In Figure 2, two blank regions appear near azimuth 245° and elevation angles of -64° and -73°, because no navigation signals exist between the main lobe and side lobe of GPS signals. Li et al. [14] noted that the TTS-2 receiver antenna has high gain across a wide beam range. The measured gain values before satellite integration are: 7.6 dB for GPS L1 signal at -30°, 10.8 dB at 0°, and 7.3 dB at 30°.

## 2.2 GPS Leakage Signal Measurement Noise

Measurement data precision significantly impacts precise orbit determination results. Using the triple-difference method between epochs [18,19], this paper calculates the noise of pseudorange and phase measurements to obtain observation data precision. The relationship between the average daily number of observations from TTS-2 and their distribution with elevation angle and noise is shown in [Figure 3: see original paper]. The elevation angle range of visible GPS signals from TTS-2 is approximately -83° to -51°. Within the elevation angle range of -81.5° to -79.5°, the noise distribution range of pseudorange/phase measurements decreases significantly. Overall, pseudorange measurement noise is mostly distributed within $±$40 m, while phase measurement noise is mostly within $±$9 cm. For pseudorange measurements, the noise distribution is relatively uniform with concentration within $±10m, showinganobviousconcentrationnear0mnoiseat −80°elevationanglewithapproximately8×10^{3}$ observations. Slight concentrations appear near -70° and -62° elevation angles. For phase measurements, concentration occurs within $±3cmnoiserange, withobviousconcentrationsnear−78°, −70°, and−62°elevationangles, wherethenumberofobservationsexceeds1.8×10^{4}$. Statistics show that from DOY 100 16:00 to DOY 108 16:00, the RMS error of pseudorange measurement noise is 7.3 m, and the RMS error of phase measurement noise is 1.3 cm.

Taking satellite G29 as an example, the relationship between pseudorange/phase measurement noise and elevation angle is shown in [Figure 4: see original paper]. From DOY 101 5:00–6:00, the pseudorange measurement noise varies within (-20, 20) m, phase measurement noise within (-4, 4) cm, while the elevation angle decreases from -67° to -73°. Starting around 6:30, satellite G29 becomes visible again to TTS-2, with elevation angle gradually decreasing from -75° to -80°, then increasing to -66°. During this period, the C1/L1 measurement noise distribution range changes with elevation angle. When elevation angle is less than -75°, the distribution ranges are $±$8 m and $±$2.2 cm for C1/L1 measurements, respectively. As elevation angle increases, the noise distribution range gradually expands. In the short period before G29 becomes invisible again, the C1/L1 measurement noise increases rapidly.

## 2.3 TTS-2 GPS Visibility and DOP

In GPS measurements, the number of visible satellites per epoch and their distribution directly affect positioning service accuracy. The Dilution of Precision (DOP) is a reference index for evaluating GPS navigation and positioning accuracy. For GEO onboard GPS measurements, the Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP) represent the precision attenuation factors in the orbital track-normal plane and radial direction, respectively. Lower DOP values indicate higher geometric positioning accuracy.

The number of visible GPS satellites per epoch, HDOP, and VDOP for the TTS-2 onboard receiver are shown in [Figure 5: see original paper]. The receiver is designed with only 8 signal channels, capable of receiving signals from up to 8 GPS satellites. For most epochs, the GEO onboard receiver can see 6–8 GPS satellites, with a few epochs seeing 4 or 5 satellites. HDOP values are mostly concentrated between 2–10, while VDOP values are concentrated between 6–30.

## 3.1 Measurement Equation

The C1/L1 measurement equations for GEO onboard GPS receivers, without considering hardware delays, can be expressed as:

$$
\begin{aligned}
C_1^s &= \rho_s + c \cdot (dt_r - dt_s) + I_{ons} + T_{rops} + \varepsilon_{C1}^s \\
L_1^s &= \rho_s + c \cdot (dt_r - dt_s) - \frac{c}{f_1^2} \cdot I_{ons} + T_{rops} + \varepsilon_{L1}^s + \lambda_{f1} \cdot N^s
\end{aligned}
$$

where $\rho_s$ represents the theoretical distance from GPS satellite $s$ antenna phase center to receiver $r$; $dt_r$ and $dt_s$ represent the clock errors of receiver $r$ and GPS satellite $s$, respectively; $c$ is the speed of light in vacuum; $I_{ons}$ and $T_{rops}$ represent ionospheric and tropospheric delays during signal propagation; $\varepsilon_{C1}^s$ and $\varepsilon_{L1}^s$ represent the noise of pseudorange $C1$ and phase $L1$ measurements for GPS satellite $s$; $\lambda_{f1}$ and $N^s$ represent the wavelength of frequency $f1$ in vacuum and the unknown ambiguity, respectively; $C_1^s$ and $L_1^s$ represent the measured pseudorange $C1$ and phase $L1$ values for GPS satellite $s$ by receiver $r$.

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## 3.2 Hardware Delay Correction

This paper processes TTS-2 onboard GPS single-frequency C1/L1 measurement data using post-processed precise orbit and clock products from the International GNSS Service (IGS). IGS products are calculated using ionosphere-free combinations of dual-frequency P1/P2 pseudorange and L1/L2 phase measurements. Therefore, when processing single-frequency C1/L1 measurement data, hardware delays for different frequency signals must be considered. The hardware delay time difference between single-frequency and dual-frequency phase measurements can be absorbed by ambiguity and receiver clock error, so phase measurement hardware delay time difference is not considered further. The differential code bias (DCB) products from the Center for Orbit Determination in Europe (CODE) are used to correct the hardware delay time difference between C1 pseudorange and dual-frequency P1/P2 pseudorange. The correction method [20] is expressed as:

$$
DCB = C_1^s + c \cdot \left( P_{1P2} - \frac{f_2^2}{f_1^2} \cdot P_{1P2} + DCB_{P1C1}^s \right)
$$

where $DCB$ represents the DCB-corrected pseudorange for GPS satellite $s$; $C_1^s$ is the original measurement; $P_{1P2}$ and $DCB_{P1C1}^s$ represent the differential code biases between pseudorange P1 and P2, and between pseudorange P1 and C1, respectively. The DCB products can be directly applied using IGS precise products.

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## 3.3 Ionospheric and Tropospheric Delay Correction

The troposphere is distributed below 20 km above Earth’ s surface, while the ionosphere is distributed between 50-1,000 km altitude. As shown in [Figure 1: see original paper], when the GEO onboard receiver acquires GPS signals at low elevation angles, the signals pass near Earth’ s surface through the ionosphere and troposphere; at high elevation angles, GPS signals are received directly without passing through these layers. Let $R_{GEO}$ be the orbital radius of the GEO satellite, and $h$ be the minimum distance from Earth’ s center to the GPS signal propagation path received by the GEO satellite. The elevation angle $ele$ of the received signal is expressed as:

$$ele = \arctan\left(\frac{h}{R_{GEO}}\right) - 90°$$

Let $R_{earth}$ be Earth’ s radius. When $(h - R_{earth})$ exceeds the ionospheric height, the navigation signals received by GEO are not affected by ionosphere and troposphere. In this paper, the cutoff elevation angle for GPS measurement data participating in orbit determination is set to -78°, eliminating navigation signal measurements that pass through the ionosphere and troposphere. After hardware delay correction and ignoring ionospheric and tropospheric delays, Equation (1) can be written as:

$$\begin{aligned} DCB &= \rho_s + c \cdot (dt_r - dt_s) + \varepsilon_{C1}^s \\ L_1^s &= \rho_s + c \cdot (dt_r - dt_s) - \lambda_{f1} \cdot N^s \end{aligned}$$

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## 4 Priori Dynamics Parameter Error Constrained Orbit Determination Mathematical Model

The motion state of a satellite at time $t$ can be expressed as:

$$[x_t, v_t] = G(x_{t0}, v_{t0}, f)$$

where $x_t, v_t$ represent the satellite’ s position and velocity at time $t$; $x_{t0}, v_{t0}$ represent the position and velocity at initial time $t0$; $f$ represents the estimated dynamic parameters; and $G$ represents the mapping function from the satellite’ s motion state at $t0$ to that at $t$. The theoretical distance $\rho_s$ in Equation (4) can be expressed as $\rho_s = H(x_t, x_s)$, where $H$ represents the mapping function from GPS satellite position $x_s$ and GEO satellite position $x_t$ to the theoretical distance. For pseudorange $L_{C1}^{DCB}(t)$ and phase $L_{L1}^s(t)$ at time $t$, we have:

$$\begin{aligned} L_{C1}^{DCB}(t) &= H[G(x_{t0}, v_{t0}, f), x_s, dt_r] + \varepsilon_{LC1}(t) \\ L_{L1}^s(t) &= H[G(x_{t0}, v_{t0}, f), x_s, dt_r, N^s] + \varepsilon_{LL1}(t) \end{aligned}$$

where $\varepsilon_{LC1}(t)$ and $\varepsilon_{LL1}(t)$ represent the measurement noise of pseudorange $L_{C1}^{DCB}(t)$ and phase $L_{L1}^{s}(t)$, respectively. Generally, when solving for the orbit, approximate values of $x_{t0}, v_{t0}$, and $f$ are first given and substituted into Equation (6) for iterative solution.

The motion state of GEO satellites is constrained by dynamics, and dynamic parameters change very little over short periods. However, the dynamic orbit determination normal equation is ill-conditioned and susceptible to observation outliers, preventing the solution from reaching optimality. GEO onboard GPS measurement data has large noise, some data contains outliers, and the noise distribution range for each satellite is unstable, easily causing the solution of the ill-conditioned normal equation to deviate from the optimal value. Therefore, this paper adopts a priori dynamics parameter error constrained orbit determination method with the following main approach.

The initial values of dynamic parameters $x_{t0}, v_{t0}$, and $f$ in orbit determination are treated as virtual observations and assigned corresponding weights based on their prior errors to participate in orbit determination. This facilitates the elimination of outliers and noisy observations during orbit processing, enabling the normal equation to obtain an optimal solution. For the observation equation system composed of Equation (6), virtual observations of initial dynamic parameters $x_{t0}, v_{t0}$, and $f$ are added:

$$\begin{aligned} L_{xt0} &= x_{t0} + V_{xt0} \\ L_{vt0} &= v_{t0} + V_{vt0} \\ L_{f} &= f + V_{f} \end{aligned}$$

where $L_{xt0}, L_{vt0}, L_f$ and $V_{xt0}, V_{vt0}, V_f$ represent the virtual observations (i.e., initial values) and corrections for initial dynamic parameters $x_{t0}, v_{t0}$, and $f$, respectively. The observation vector of the model is:

$$[L_{xt0}, L_{vt0}, L_f, L_{C1}^{DCB}(t_1), \dots, L_{C1}^{DCB}(t_n), L_{L1}^{s}(t_1), \dots, L_{L1}^{s}(t_n)]$$

The weight matrix of the observation vector is:

$$\operatorname{diag}\left(\frac{1}{\sigma_{xt0}^2}, \frac{1}{\sigma_{vt0}^2}, \frac{1}{\sigma_f^2}, \frac{1}{\sigma_{C1}^2(t_1)}, \dots, \frac{1}{\sigma_{C1}^2(t_n)}, \frac{1}{\sigma_{L1}^2(t_1)}, \dots, \frac{1}{\sigma_{L1}^2(t_n)}\right)$$

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## 5.1 Orbit Determination Strategy and Experimental Design

This paper employs the priori dynamics parameter error constrained orbit determination method to process orbits using different constraint strategies for dynamic parameters, evaluating orbit determination accuracy. Three experiments were designed with specific analysis procedures as follows:

1. **Test-1**: Constraining dynamic parameters including initial satellite position, velocity, and 5 solar radiation pressure parameters. Using the orbit determination solution parameters and their standard errors from the previous adjacent arc as initial values and errors ($\sigma$) for the current orbit determination; all estimated parameter errors use either $1\sigma$ (Test-1a) or $3\sigma$ (Test-1b).
2. **Test-2**: Constraining only the 5 solar radiation pressure parameters. Using the orbit determination solution parameters and their standard errors from the previous adjacent arc as initial values and errors ($\sigma$); the 5 solar radiation pressure parameter errors use either $1\sigma$ (Test-2a) or $3\sigma$ (Test-2b).
3. **Test-3**: Constraining the 5 solar radiation pressure parameters. Using the average values of the solar radiation pressure parameters and their standard errors from Test-1a as initial values and errors ($\sigma$); the 5 solar radiation pressure parameter errors use either $1\sigma$ (Test-3a) or $3\sigma$ (Test-3b).

At the beginning of the experiments, the first dataset of Test-1a was iteratively solved to obtain dynamic parameters with initial position standard errors less than 5 cm, which were used as prior values for the first orbit determination in all three experiments.

The measurement and dynamic models used for orbit determination in this paper are listed in .

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## 5.2 Experimental Results and Analysis

The orbit determination data spans from DOY 100 16:00 to DOY 108 16:00, 2018. Both 72-hour and 36-hour arc orbit determinations were performed. For 72-hour arc orbit determination (from Day 0 16:00 to Day 4 16:00), six orbit solutions were obtained. For 36-hour arc orbit determination (from Day 0 16:00 to Day 3 04:00), seven orbit solutions were obtained.

The pseudorange/phase measurement residuals and data effective rates after orbit determination for each experiment are summarized in . For 72-hour arc orbit determination, the observation data effective rate is about 85%, with pseudorange measurement RMS residuals around 537.8 cm and phase measurement RMS residuals around 5.6 cm. The data effective rates and RMS residuals of C1/L1 measurements differ little among experiments. For 36-hour arc orbit determination, the RMS residual of C1 measurements is about 523.4 cm, L1 measurement RMS residual is 5.3 cm, and the observation data effective rate is 85%.

For 72-hour arc orbit determination with 48-hour overlap, there are five overlapping arcs. When comparing each overlapping arc, to avoid edge effects, the middle 24 hours of the overlapping arc are used for comparison. For 36-hour arc orbit determination with 12-hour overlap, there are six overlapping arcs, and the middle 6 hours are used for comparison. The RMS errors in three-dimensional, radial, along-track, and cross-track directions for each experiment' s overlapping arcs are shown in [Figure 6: see original paper] (72-hour arcs) and [Figure 7: see original paper] (36-hour arcs).

In the 72-hour arc orbit determination overlap comparison shown in [Figure 6: see original paper], Test-1a and Test-1b (with constrained motion state) both achieve three-dimensional RMS errors less than 1 m and radial RMS errors less than 0.2 m. Test-2a, Test-2b, and Test-3a (constraining only solar radiation pressure parameters) show larger three-dimensional RMS errors but still maintain radial RMS errors less than 0.3 m. Test-3b shows three-dimensional RMS errors around 0.65 m with radial RMS errors less than 0.3 m. A notable feature is that orbit solutions with constrained satellite motion state parameters achieve better overlap consistency, with significantly reduced cross-track RMS errors.

In the 36-hour arc orbit determination overlap comparison shown in [Figure 7: see original paper], Test-1a (with constrained motion state) achieves three-dimensional RMS errors less than 0.8 m and radial RMS errors less than 0.2 m. Test-1b shows larger RMS errors in the last three overlapping arcs but maintains overall three-dimensional RMS errors below 1 m. Tests-2a, 2b, 3a, and 3b (constraining only solar radiation pressure parameters) show three-dimensional RMS errors of 0.9–1.5 m. Similar to 72-hour arc results, orbit solutions with constrained satellite motion state parameters demonstrate better overlap consistency with the lowest cross-track RMS errors.

To more specifically evaluate the orbit determination results using TTS-2 onboard GPS single-frequency data, the overall orbit overlap RMS errors for Test-1, Test-2, and Test-3 are summarized in . With satellite motion state parameter constraints, both 72-hour and 36-hour arc orbit determinations achieve three-dimensional RMS errors less than 0.65 m, with radial RMS errors less than 0.2 m for 72-hour arcs and less than 0.3 m for 36-hour arcs. With only solar radiation pressure parameter constraints, using $3\sigma$ prior error constraints yields better orbit overlap consistency. Overall, the orbit overlap consistency for 72-hour arc determination is better than 1 m, and for 36-hour arc determination is better than 1.5 m. Compared with the orbit determination results in [15, 16], the orbit overlap consistency has improved by more than 40%.

## 6 Conclusions

Using TTS-2 onboard GPS observation data as an example, this paper analyzes GEO onboard GPS single-frequency C1/L1 data and conducts experiments using the priori dynamics parameter error constrained orbit determination method. The main conclusions are:

1. GEO onboard GPS data noise has a large distribution range and shows correlation with elevation angle. Obvious data clustering occurs near elevation angles of -78°, -70°, and -62°. The GEO onboard receiver can see 6–8 GPS satellites during most epochs, with HDOP values concentrated between 2–10 and VDOP values between 6–30.
2. The orbit overlap consistency of GEO satellite orbit determination using onboard GPS single-frequency data is about 1 m, with optimal performance reaching sub-meter level. With constrained satellite motion state parameters, both 72-hour and 36-hour arc orbit determinations achieve overlap consistency better than 0.65 m. With only solar radiation pressure parameter constraints, the three-dimensional RMS error is 1.0 m for 72-hour arc orbit determination and less than 1.5 m for 36-hour arc orbit determination.
3. Experiments demonstrate that reasonable setting of dynamic parameter errors using the priori dynamics parameter error constrained orbit determination method can yield orbit solutions with better overlap consistency.

The orbit determination methods, research content, and results in this paper provide valuable reference for high-precision applications of onboard GNSS on high-orbit spacecraft. The establishment of the BeiDou global navigation satellite system will provide better solutions for onboard GNSS navigation and precise orbit determination of high-orbit spacecraft. Additionally, the noise in high-orbit spacecraft onboard GNSS data is relatively large, and its error sources require further study. Challenges remain for decimeter-level or even centimeter-level high-precision orbit determination of high-orbit spacecraft, necessitating continued in-depth research.

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*Note: Figure translations are in progress. See original paper for figures.*