Postprint: Research on SpaceX Starlink Satellite Ephemeris Publication

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Abstract

Faced with the current situation where Starlink satellites severely interfere with normal space activities, the Starlink ephemeris released by SpaceX has brought opportunities for research related to Starlink satellites, but the lack of clear documentation also poses difficulties for further use. Analysis of the ephemeris files reveals that the ephemeris is essentially predicted orbits for the next 3;d. Mean element studies indicate that the first part of the ephemeris file consists of extrapolated orbits that consider at least 20th-order non-spherical gravitational perturbations, while the latter part comprises design orbits considering J_2 perturbation terms. The ephemeris includes covariance information. Analysis shows that the ephemeris for satellites in parking and operational orbits achieves an accuracy better than 2;km for the first day, whereas the accuracy of ephemeris for satellites in the orbit-raising phase rapidly degrades to several kilometers within less than half a day. Through the published design orbits in the ephemeris, the Starlink constellation configuration can be analyzed more precisely, especially the designed slot positions of each satellite, which facilitates the identification and tracking of Starlink satellites. This study provides a useful reference for the widespread application of Starlink ephemeris and offers a basis for maneuver detection and collision warning of Starlink satellites.

Full Text

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Abstract

Faced with the significant disruption of normal space activities caused by Starlink satellites, the ephemeris data published by SpaceX provides valuable opportunities for related research, though the lack of clear documentation presents challenges for effective utilization. Analysis of the ephemeris files reveals that they primarily represent predicted orbits for the next three days. Research using mean orbital elements indicates that the initial portion of each ephemeris file represents an extrapolated orbit accounting for non-spherical gravitational perturbations up to at least 20th order, while the latter portion represents a design orbit considering only J2 perturbation. The ephemeris includes covariance information, which enables accuracy assessment. Analysis shows that for satellites in parking and working orbits, the ephemeris accuracy is better than 2 km for the first day, whereas for satellites in the raising phase, the accuracy degrades rapidly to several kilometers within half a day. Utilizing the design orbit information from the published ephemeris enables more precise analysis of the Starlink constellation configuration, particularly the designated positions of individual satellites, which facilitates identification and tracking. This study provides a valuable reference for the broad application of Starlink ephemeris data and offers a foundation for maneuver detection and collision warning efforts.

Keywords: celestial mechanics, space vehicles: Starlink, ephemerides, methods: mean element, methods: data analysis

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1. Introduction

With the advancement of space technology and the expansion of the space industry, global commercial space activities have developed rapidly. Companies such as SpaceX, OneWeb, and Amazon have proposed large-scale low-Earth orbit (LEO) communication constellation plans [1]. Among these, SpaceX's Starlink constellation has become the world's largest LEO mega-constellation. According to materials submitted by SpaceX to the U.S. Federal Communications Commission (FCC), the company plans to launch a total of 42,000 LEO satellites, with 12,000 currently approved. SpaceX intends to construct five orbital shells at altitudes of 540–570 km, with adjacent shells separated by 10 km. As of July 31, 2023, the construction plan and launch status for the first phase of Starlink are shown in .

Based on the launch status of each shell, Shell 1 has completed 29 launches with 1,725 satellites, representing SpaceX's first deployed constellation, while Shell 4 has completed 32 launches with 1,637 satellites, forming the second major deployed constellation. Notably, the number of launched satellites for both shells exceeds their planned totals, likely because some Starlink satellites have re-entered the atmosphere due to mechanical failures or geomagnetic storms [2].

Starlink satellites are launched using reusable Falcon 9 rockets. At approximately 300 km altitude, a special release mechanism deploys the satellites, after which they enter a parking orbit near 350 km. Using krypton ion thrusters, the satellites then raise their orbits, eventually reaching working altitudes of 550 km (Shell 1) or 540 km (Shell 4). Consequently, Starlink satellites experience three primary operational phases: parking, raising, and working.

Since the first Starlink launch on May 24, 2019, SpaceX had conducted 95 launches deploying 4,867 satellites as of July 31, 2023. This massive satellite system not only affects astronomical observations [3] but also poses significant collision threats to LEO spacecraft. On September 2, 2019, the European Space Agency (ESA) performed an emergency avoidance maneuver to prevent collision between its Aeolus weather satellite and Starlink-44. On April 3, 2020, a close approach event occurred between Starlink-1546 and OneWeb-017B. On December 3, 2021, China's Permanent Mission to the United Nations in Vienna reported two close approach events between Starlink satellites and the Chinese Space Station (Starlink-1095 on July 1, 2021, and Starlink-2305 on October 21, 2021). These incidents demonstrate that Starlink satellites have seriously interfered with normal space activities, a problem likely to intensify with future LEO constellation deployments.

To mitigate collision risks, accurate orbital information is essential for assessing collision probability. However, due to the large number of Starlink satellites, tracking measurements are limited by equipment availability, observation modes, operational capacity, and station distribution, making it difficult to obtain high-precision ephemerides for the entire constellation. The North American Aerospace Defense Command (NORAD) publishes catalog orbital data for Starlink satellites in Two-Line Element (TLE) format on the Space-track website. TLE data are widely used for space situational awareness and collision warning due to their completeness, openness, and timeliness. Reference [4] analyzed the accuracy of Starlink TLE data using internal consistency methods, finding position errors of less than 3 km for one-day predictions for parking and working orbit satellites, and less than 8 km for raising phase satellites. This study also validated collision probability calculations for four operational phases, providing references for collision warning. Reference [5] proposed a recursive matching method using TLE data to associate sparse observations with unknown maneuvering satellites during the orbit-raising phase, offering insights for precise orbit determination and prediction.

Although TLE data serve a role in collision warning, frequent maneuvers by Starlink satellites result in low prediction accuracy, and TLE data lack precision or covariance information for orbital elements, failing to meet practical requirements. To address urgent needs in international space launch and collision warning, SpaceX began publishing Starlink ephemeris data in May 2021, providing better conditions for observation matching, constellation positioning, configuration analysis, and collision warning research. However, the lack of clear documentation creates difficulties for users, necessitating preliminary analysis of naming conventions, data composition, and accuracy to enable proper and effective utilization.

This paper introduces the current status of the Starlink constellation, clarifies the meaning of SpaceX's ephemeris filenames, examines the data content, preliminarily analyzes the prediction models using mean element methods, presents the orbital accuracy for three operational phases, and uses the theoretical design orbit from the ephemeris to determine satellite positions and constellation configuration.

2.1 Publication and Format Description of Starlink Ephemeris

In May 2021, to meet the needs of international space activities and LEO satellite collision warning, SpaceX began publishing Starlink ephemeris on its website. SpaceX releases ephemeris three times daily, with updates approximately every eight hours. The data are stored in multiple compressed files, each up to about 1 GB in size, with current releases comprising 2–4 compressed packages.

Decompressing the packages reveals numerous files, each corresponding to one satellite. A typical filename format is: `MEME_{{{3879600}}_{{UNCLASSIFIED}}}.txt`, containing seven fields separated by underscores. While clearly valuable for maneuver strategy analysis and collision warning research, SpaceX has not released documentation for this ephemeris format, necessitating analysis of its structure and accuracy.

Space-track, operated by the U.S. Joint Space Operations Center, establishes rules for external ephemeris filename formats and data structures, requiring satellite operators to comply with these standards [6]. Analysis of Starlink ephemeris filenames reveals their structure as shown in .

Each Starlink ephemeris file contains a header and thousands of data blocks. [Figure 1: see original paper] illustrates the header and first data block. The four-line header indicates creation time, start and stop times, orbit source, and coordinate system, while data blocks provide epoch times, satellite state vectors, and covariance information, as detailed in .

The covariance matrix is stored in lower-triangular format, with the arrangement for the first data block shown in [Figure 2: see original paper]. The header shows a 60-second epoch interval and a three-day time span, yielding 4,321 data blocks per file. Creation times are typically 10–30 minutes after the ephemeris start time. For example, one file starts at UTC 2022-11-27 21:39:42, with creation at UTC 2022-11-27 22:02:31—only about 20 minutes later. This confirms that SpaceX's published ephemeris represents predicted orbits for the next three days rather than post-processed precise ephemerides.

2.2 Analysis of the Published Ephemeris Model

The ephemeris header indicates use of a "blend" propagation model, whose details are important for proper utilization. For LEO satellites like Starlink, Earth's non-spherical gravitational perturbations dominate orbital element variations. Converting satellite state data from the ephemeris into quasi-mean elements under different Earth gravity field orders [7][8] enables preliminary analysis of the gravity field order used in extrapolation. Quasi-mean elements are osculating elements with short-period variations from major perturbations removed. Eliminating these phase differences, the mean semi-major axis remains essentially stable (in a first-order sense) except for slight decay from atmospheric drag, provided appropriate gravity field orders are used.

Satellite orbits are typically described using Keplerian elements (a, e, i, Ω, ω, M), where e is eccentricity, i is inclination, Ω is right ascension of the ascending node, ω is argument of perigee, and M is mean anomaly. However, Starlink satellites operate in near-circular orbits with small eccentricities, making Keplerian elements singular. To address this, we introduce non-singular elements of the first kind (a, i, Ω, , , λ) [9], defined as: = e cos ω = e sin ω λ = M + ω

Using the November 29, 2022 ephemeris for Starlink-1007 in a 550 km working orbit as an example, we analyzed variations in the mean semi-major axis. [Figure 3: see original paper] shows the mean semi-major axis considering only J2 perturbation over three days; [Figure 4: see original paper] shows the latter 1.5 days with J2–J4 perturbations; and [Figure 5: see original paper] shows the mean semi-major axis with high-order Earth gravity field perturbations (20$×$20 order) over three days.

Comparison reveals that the mean semi-major axis in the last 1.5 days remains stable only in [Figure 3: see original paper], with minimal amplitude variation of just 10 m. Applying this method to different satellites, times, and phases yields results shown in [Figure 6: see original paper] and the Appendix. The left column in these figures considers only J2 perturbation, while the right column uses up to 20$×$20 order gravity field, both over three days. The results demonstrate that the latter portion of the ephemeris shows minimal variation only under J2 perturbation, indicating it represents a theoretical design orbit considering only J2 perturbation—consistent with design philosophy for most LEO satellites [10].

Statistical analysis of multiple satellites reveals that for working and parking phase ephemerides, the propagation model changes abruptly at approximately 1.5 days, with the latter 1.5 days being J2-only design orbits. For raising phase satellites, the design orbit dominates most of the prediction span (approximately 2.75 days), likely due to continuous thrusting during orbit raising, where frequent maneuvers make other perturbations relatively insignificant. This simplifies calculations while reflecting orbital evolution.

Further comparison shows that the initial portion of the ephemeris exhibits amplitude variations exceeding 100 m under J2-only perturbation, becoming unstable. With 20$×20ordergravityfieldperturbations,theamplitudeimprovestobetterthan10m.Todeterminetheex
orderanalysisonworkingandparkingphaseephemerides : calculatingfirst − orderanalyticalsolutionsforgravityfieldsfrom5×5to35×$35 orders, performing linear fitting on the first 1.5 days of mean semi-major axis data, and computing RMS residuals.

presents RMS values for different satellites and gravity field orders. The first six rows correspond to 2022 ephemerides, showing that RMS residuals decrease with increasing order, stabilizing at 20th order and above. This suggests the initial portion uses an extrapolated orbit accounting for non-spherical gravitational perturbations to at least 20th order.

Analysis of multiple ephemeris releases shows that working and parking phase ephemerides use high-order gravity field extrapolation for approximately 1.5 days, though some use less than one day. Since January 2023, SpaceX adjusted the ephemeris format, as shown in [Figure 7: see original paper] and the Appendix. The right panel of [Figure 7: see original paper] shows mean semi-major axis amplitude better than 10 m for the first two days under 20th-order perturbation. The last six rows of show similar RMS patterns for 2023 ephemerides, indicating SpaceX extended the high-order extrapolation period to two days for all three operational phases while maintaining the same gravity field order.

2.3 Internal Accuracy Analysis of Published Ephemeris

Starlink orbit prediction accuracy is critical for space missions and collision avoidance. The published ephemeris includes covariance information, enabling self-assessment of prediction accuracy. As described in Section 1, Starlink satellites experience three operational phases with distinct altitude characteristics: parking orbit near 350 km, raising orbit between 350–550 km with increasing altitude, and working orbit at approximately 540 km or 550 km depending on the shell. Different control and perturbation factors in each phase may affect prediction accuracy differently, requiring separate analysis.

We randomly downloaded 3,184 Starlink ephemeris files published on November 29, 2022, containing three-day predictions and covariance information. Based on altitude characteristics, we classified them into 98 parking orbit, 144 raising orbit, and 2,878 working orbit satellites. An additional 64 satellites exhibited different altitude profiles, including some with descending altitudes or stationed at waypoint orbits, requiring separate discussion.

Focusing on the three main phases, we extracted the first, third, and sixth covariance values at each epoch and computed their square roots to obtain self-assessed prediction errors in the U, V, and W directions. Initial examination revealed similar accuracy trends within each phase. To avoid statistical bias from transitional states, we applied a 3σ criterion to exclude outliers, where σ represents the standard deviation of position errors, then computed mean prediction errors.

– present the evolution of mean prediction errors for parking, raising, and working orbit satellites, while [Figure 8: see original paper]–[Figure 10: see original paper] show error evolution in U, V, and W directions (using logarithmic scales for clarity). The results show that ephemeris accuracy degrades from several meters to kilometers over the prediction span. Parking and working orbit satellites achieve better than 2 km accuracy in the first day, while raising orbit satellites degrade to kilometer-level errors within half a day. In all phases, V-direction (along-track) errors dominate, with smaller U and W errors, consistent with the inherent instability of along-track orbit prediction.

[Figure 8: see original paper] and [Figure 10: see original paper] show abrupt error jumps near 1.5 days, confirming the transition between different propagation models. The latter 1.5 days use J2-only perturbation with fixed covariance values, resulting in constant prediction errors. SpaceX likely uses different models to balance user needs and operational efficiency, ensuring ephemeris generation efficiency while meeting accuracy requirements. High-precision ephemeris errors reach approximately 5 km after 1.5 days, sufficient for user needs. Continuing high-order perturbation calculations for the latter 1.5 days would consume substantial computational resources for the large Starlink constellation while providing no accuracy advantage over the design orbit.

For the raising phase, [Figure 9: see original paper] shows rapid error divergence to 2 km after 0.15 days, consistent with the model transition inferred earlier. Errors peak around 0.25 days then stabilize, indicating the raising orbit prediction characteristics.

The 2023 ephemeris format change also affects error evolution. [Figure 11: see original paper]–[Figure 13: see original paper] show error statistics for 3,822 ephemeris files published on January 26, 2023. SpaceX again uses fixed covariance values, with parking orbit errors approaching the fixed values at about 1 day, raising orbit at 0.25 days, and working orbit at 1.5 days. All phases show abrupt error transitions near 2 days, consistent with the model change in 2023 ephemerides.

3. Preliminary Applications of Published Ephemeris

Starlink constellation systems consist of multiple satellites forming stable spatial configurations with fixed spatiotemporal relationships to enable rapid global communication coverage. Constellation configuration is fundamental, determining coverage characteristics, operational performance, and maintenance capabilities [11]. While researchers have analyzed Starlink configuration using TLE data—for example, Xue et al. [12] discussed deployment based on batches 2–13 using Walker-δ constellations—these analyses lacked individual satellite position and accuracy information.

Our study reveals that the published ephemeris contains theoretical design orbits considering only J2 zonal harmonic perturbation, which is highly advantageous for studying the large Starlink system. This enables more accurate constellation configuration analysis, including nominal satellite positions at specific times. Comparing these nominal positions with determined satellite positions can improve understanding of maneuver triggering mechanisms and strategies.

Starlink uses Walker-δ constellation configurations [13], characterized by uniformly distributed argument of latitude within each orbital plane (identical right ascension of ascending node) and equally spaced ascending nodes across planes with identical inclination. The structure is typically denoted T/P/F, where T is total satellite count, P is number of orbital planes, and F is the phase factor representing relative phasing between adjacent planes. The ascending node spacing $\Delta\Omega$ and phase difference Δu between corresponding satellites in adjacent planes are: $\Delta\Omega = 2\pi/\mathrm{P}$ $\Delta\mathrm{u} = 2\pi\mathrm{F}/\mathrm{T}$

Shell 1, SpaceX's first deployed constellation, has design parameters of 1,584 satellites at 550 km altitude, 53° inclination, and 72 orbital planes. To determine its configuration parameters, we used the latter 1.5 days of ephemeris from February 26, 2023, extrapolated all satellites to a common epoch (UTC 2023-03-02 05:10:22) using mean elements to account for J2-induced periodic variations, and analyzed the 1,446 operational satellites in Shell 1. [Figure 14: see original paper] shows the latitude distribution across orbital planes. The distribution is uniform, with approximately 5° spacing between adjacent ascending nodes and 18–22 satellites per plane. Each plane contains approximately 18 satellites uniformly distributed in argument of latitude from 0–360°, designated as operational satellites. statistics show phase differences between adjacent operational satellites of essentially 20°, with errors mostly below 0.1°.

With few exceptions, most planes contain 18 uniformly distributed satellites. We conclude Shell 1 has 1,296 operational satellites, with 1–4 additional backup satellites per plane positioned 5° from adjacent operational satellites. When operational satellites fail, nearby backup satellites maneuver to replace them, restoring constellation configuration and ensuring coverage performance.

The 12.5° phase difference between corresponding satellites in adjacent planes yields a phase factor of 45. Therefore, Shell 1's configuration is Walker-δ type:

1,296/72/45: (53°, 550 km), closely matching the deployment plan.

Shell 4, SpaceX's second major constellation, has design parameters of 1,584 satellites at 540 km altitude, 53.2° inclination, and 72 planes. Using the same method for UTC 2023-03-02 05:10:22 with 1,550 operational satellites in Shell 4 yields similar distribution results. Shell 4's configuration is essentially identical to Shell 1, differing only in altitude and inclination: 1,296/72/45: (53.2°, 540 km).

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4. Conclusion

This study addresses the collision threat posed by Starlink satellites to LEO spacecraft through analysis of SpaceX-published ephemeris data. We examined filename conventions, finding the ephemeris represents primarily three-day predicted orbits. Using mean element methods, we determined the initial portion uses Earth gravity field extrapolation to at least 20th order, while the latter portion uses J2-only theoretical design orbits. Based on distinct altitude characteristics during parking, raising, and working phases, we analyzed ephemeris accuracy in U, V, and W directions. Parking and working orbit ephemerides achieve better than 2 km accuracy in the first day, while raising phase ephemeris remains within 500 m for 0.1 days before rapidly degrading to 2 km after 0.15 days. Using the design orbit information, we determined satellite nominal positions and analyzed constellation configuration, confirming Shell 1 deployment as 1,296/72/45: (53°, 550 km) and Shell 4 as 1,296/72/45: (53.2°, 540 km). This research provides valuable references for expanded application of Starlink ephemeris data, maneuver strategy analysis, and collision warning avoidance.

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