Real-Time Ephemeris Update Mechanism for Effective Doppler and Timing Pre-Compensation in 5G NR-NTN gNB

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***Abstract*—Non-Terrestrial Networks (NTN) are an important feature of 5G NR that extends cellular connectivity through satellites. A major issue is the strong Doppler shift and variable propagation delay caused by fast-moving satellites, especially in Low Earth Orbit (LEO). 3GPP specifies that Operation and Maintenance (OAM) shall provide ephemeris (orbital trajectory information) data to the gNB. The gNB needs to pre-compensate the Doppler and Timing Advance (TA) before sending any residual corrections to the UE via SIB19. This paper develops a mathematical model that explains how outdated ephemeris data (i.e., inaccurate satellite position/velocity information) causes errors in Doppler shift and Timing Advance estimates at the gNB/UE. We show that short update intervals of 1 to 5 seconds are enough for LEO at 2 GHz. However, using higher carrier frequencies or longer update gaps leads to significant residuals. Simulations of LEO, MEO, and GEO orbits provide design guidelines for ephemeris update timing. The results highlight the importance of real-time ephemeris delivery and demonstrate the trade-offs between update frequency, signalling cost and UE performance.**

***Index Terms*—Non-Terrestrial Networks (NTN), Ephemeris Updates, Doppler Pre-compensation, Timing Advance, SIB19.**

I. Introduction

Non-Terrestrial Networks (NTN) extend 5G New Radio (NR) to provide connectivity in remote, rural, maritime, and aerial environments where terrestrial infrastructure is limited [1], [2]. Low Earth Orbit (LEO) satellite constellations, in particular, offer low latency and high capacity, but introduce significant challenges due to large and rapidly time-varying Doppler shifts and propagation delays, which complicate synchronization and uplink timing alignment at the user equipment (UE) [3], [4].

To address these challenges, 3GPP Release 17 introduces NTN support within the NR framework, building upon earlier NTN studies in 3GPP TR 38.821 [5]. The specification requires Operation and Maintenance (OAM) entities to provide satellite ephemeris information to the gNB, which performs Doppler and Timing Advance (TA) pre-compensation and broadcasts assistance to UEs via System Information Block 19 (SIB19) [6]. SIB19 enables NTN-capable UEs to maintain synchronization despite satellite mobility. However, 3GPP does not specify how frequently ephemeris updates should be delivered or how ephemeris staleness impacts residual Doppler and TA errors across different orbital regimes.

Existing studies on NTN primarily focus on Doppler mitigation and synchronization, often assuming perfect or continuously updated ephemeris information [1], [3]. Consequently, the impact of outdated ephemeris data—an unavoidable practical limitation—remains insufficiently explored, particularly in terms of its effect on residual synchronization errors.

This paper addresses this gap by developing an analytical framework that quantifies the impact of ephemeris staleness on Doppler and TA pre-compensation in 5G NR-NTN systems. Closed-form expressions are derived to relate residual errors to orbit parameters, carrier frequency, and update intervals. The analysis is validated using SGP4-based simulations and Monte Carlo methods across LEO, MEO, and GEO scenarios. The results provide practical design guidelines for ephemeris update intervals and SIB19 validity, bridging the gap between 3GPP specifications and real-world NTN deployments.

TABLE I
Comparison of Proposed Work with Existing Literature

Reference	**Ephemeris Staleness**	**TA Modeling**	**Analytical Bounds**
Islam et al. [3]	Not considered	Not considered	Not provided
Liu et al. [7]	Implicit consideration	Partial modeling	Not provided
This Work	Explicit modeling	Yes	Closed-form bounds

II. Contributions

The contributions of this paper are summarized as follows:

- **Analytical Error Modeling:** We develop a first-order mathematical framework that explicitly maps satellite position and velocity estimation errors arising from ephemeris staleness into residual Doppler shift and Timing Advance (TA) errors observed at the gNB and UE.
- **Closed-Form Update Interval Bounds:** We derive compact scaling laws that relate acceptable ephemeris update

periodicity to orbit altitude, satellite acceleration, and carrier frequency, providing clear design rules for LEO, MEO, and GEO NTN scenarios.

- **Simulation and Statistical Validation:** Using SGP4-based orbit propagation and Monte Carlo simulations over random UE locations and line-of-sight (LOS) geometries, we validate the analytical bounds and demonstrate their conservativeness under realistic deployment assumptions.

- **System-Level Design Insights:** We discuss practical trade-offs between ephemeris update frequency, OAM/O1 signaling overhead, and SIB19 validity durations, offering actionable guidance for 3GPP-compliant NR-NTN implementations.

III. System Architecture and Data Flow

This section describes the system-level architecture and the flow of ephemeris information used for Doppler and Timing Advance pre-compensation in NR-NTN.

A. Pipeline Overview

1) Ephemeris ingestion from TLE/OEM/SP3 sources.
2) Propagation using SGP4 to obtain state vectors (position, velocity).
3) OAM push to gNB via O1 interface.
4) gNB performs Doppler/TA pre-compensation.
5) gNB broadcasts assistance to UEs via SIB19.

B. System Diagram

Fig. 1 shows the conceptual architecture of the proposed solution.

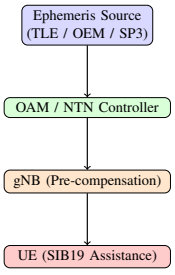

Fig. 1. Proposed pipeline for real-time ephemeris updates in 5G NR-NTN.

C. Ephemeris Data Flow in NTN:

In non-terrestrial networks (NTN), accurate satellite trajectory information is essential for Doppler compensation, propagation-delay estimation, and mobility management. This information flows through a structured chain starting from external ephemeris sources and ending at the user equipment (UE) through the gNB. Ephemeris sources provide satellite position, velocity, and timing data in formats such as TLE, OEM, or SP3. These datasets allow precise orbit prediction, with update rates ranging from minutes to hours.

The O&M system collects this ephemeris data through the O1 interface, validates it, and converts it into 3GPP-compliant structures before sending it to the gNB.

The gNB, located either on the ground or onboard the satellite, uses the ephemeris to perform Doppler pre-compensation and timing-advance adjustments. It also anticipates beam movement to support mobility.

Finally, the UE receives assistance information via SIB19, enabling improved synchronization, Doppler tracking, and initial access.

IV. System Model and Mathematical Framework

We consider a satellite-enabled NTN system in which the gNB performs Doppler and Timing Advance (TA) pre-compensation using ephemeris information provided via the OAM interface. The satellite state is obtained from standard ephemeris formats (e.g., TLE) and propagated using the SGP4 model to obtain position $\mathbf{r}_{\text{sat}}(t)$ and velocity $\mathbf{v}_{\text{sat}}(t)$ in the Earth-centered inertial (ECI) frame.

The UE state is denoted by $\mathbf{r}_{\text{UE}}(t)$ and $\mathbf{v}_{\text{UE}}(t)$. The relative position and line-of-sight (LOS) unit vector are defined as

$$\mathbf{r}_{\text{rel}}(t) = \mathbf{r}_{\text{sat}}(t) - \mathbf{r}_{\text{UE}}(t), \tag{1}$$

$$\hat{\mathbf{u}}(t) = \frac{\mathbf{r}_{\text{rel}}(t)}{\|\mathbf{r}_{\text{rel}}(t)\|}. \tag{2}$$

The instantaneous relative radial velocity is given by

$$v_{\text{rel}}(t) = (\mathbf{v}_{\text{sat}}(t) - \mathbf{v}_{\text{UE}}(t)) \cdot \hat{\mathbf{u}}(t). \tag{3}$$

The Doppler shift at carrier frequency f_c is

$$f_d(t) = \frac{f_c}{c} v_{\text{rel}}(t), \tag{4}$$

where c is the speed of light. The timing advance (TA) is computed as

$$TA(t) = \frac{2\|\mathbf{r}_{\text{rel}}(t)\|}{c}. \tag{5}$$

A. Ephemeris Error Model

The gNB relies on an estimated satellite state $\hat{\mathbf{r}}_{\text{sat}}(t)$ and $\hat{\mathbf{v}}_{\text{sat}}(t)$, which may be outdated due to ephemeris staleness. The resulting estimation errors are defined as

$$\Delta\mathbf{r}(t) = \mathbf{r}_{\text{sat}}(t) - \hat{\mathbf{r}}_{\text{sat}}(t), \tag{6}$$

$$\Delta\mathbf{v}(t) = \mathbf{v}_{\text{sat}}(t) - \hat{\mathbf{v}}_{\text{sat}}(t). \tag{7}$$

Using first-order linearization, the residual Doppler error after pre-compensation is approximated as

$$\Delta f_d(t) \approx \frac{f_c}{c}\left(\Delta\mathbf{v}(t)\cdot\hat{\mathbf{u}}(t) + \frac{(\mathbf{v}_{\text{sat}} - \mathbf{v}_{\text{UE}})^T(I - \hat{\mathbf{u}}\hat{\mathbf{u}}^T)\Delta\mathbf{r}(t)}{\|\mathbf{r}_{\text{rel}}(t)\|}\right). \tag{8}$$

Similarly, the residual timing advance error is

$$\Delta TA(t) \approx \frac{2}{c}\hat{\mathbf{u}}(t)\cdot\Delta\mathbf{r}(t). \tag{9}$$

B. Error Growth due to Ephemeris Staleness

If the satellite state is propagated from an earlier epoch t_0 to $t = t_0 + \Delta t$, the dominant error terms are approximated as

$$\Delta \mathbf{v}(t) \approx \mathbf{a}_{\text{sat}}(t_0)\Delta t, \tag{10}$$

$$\Delta \mathbf{r}(t) \approx \mathbf{v}_{\text{sat}}(t_0)\Delta t. \tag{11}$$

Substituting into the Doppler expression yields the scaling law

$$\Delta f_d(t) \approx \frac{f_c}{c}(\mathbf{a}_{\text{sat}} \cdot \hat{\mathbf{u}})\Delta t, \tag{12}$$

and for timing advance

$$\Delta TA(t) \approx \frac{2}{c}(\hat{\mathbf{u}} \cdot \mathbf{v}_{\text{sat}})\Delta t. \tag{13}$$

The proposed framework adopts a first-order conservative approximation in which position errors grow as $\Delta r \approx v_{sat}\Delta t$. Higher-order effects associated with orbital acceleration (e.g., $\frac{1}{2}a\Delta t^2$) are neglected and may become relevant only for larger update intervals. Therefore, the derived expressions should be interpreted as first-order design guidelines for practical NTN deployments.

C. Numerical Example

For a representative LEO satellite, $\|\mathbf{v}_{\text{sat}}\| \approx 7.5 \times 10^3$ m/s and $\|\mathbf{a}_{\text{sat}}\| \sim 8$ m/s^2. For $f_c = 2$ GHz and $\Delta t = 1$ s,

$$\Delta f_{d,a} \approx \frac{2 \times 10^9}{3 \times 10^8} \times 8 \times 1 \approx 53 \text{ Hz}. \tag{14}$$

Compared to the uncompensated Doppler $f_d \sim (v/c)f_c \approx 50$ kHz, a 1-second staleness produces a small residual, implying update intervals of a few seconds suffice. A practical guideline is

$$\Delta t_{\max} \approx \frac{f_{d,\max_allowed}\, c}{f_c\, (\mathbf{a}_{\text{sat}} \cdot \hat{\mathbf{u}})}. \tag{15}$$

D. Covariance Propagation

If the ephemeris provider supplies a covariance $P_{r,v}(t_0)$ at epoch t_0, its propagation yields an error covariance $P(t)$. The residual variances of Doppler and TA can be approximated as

$$\mathrm{Var}(\Delta f_d) \approx \left(\tfrac{f_c}{c}\right)^2 \Bigg(\hat{\mathbf{u}}^{\mathsf{T}} P_v \hat{\mathbf{u}} + \frac{\mathbf{v}_{\text{rel}}^{\mathsf{T}}(\mathbf{I} - \hat{\mathbf{u}}\hat{\mathbf{u}}^{\mathsf{T}})\, P_r\, (\mathbf{I} - \hat{\mathbf{u}}\hat{\mathbf{u}}^{\mathsf{T}})\mathbf{v}_{\text{rel}}}{\|\mathbf{r}_{\text{rel}}\|^2} \Bigg), \tag{16}$$

$$\mathrm{Var}(\Delta TA) \approx \left(\tfrac{2}{c}\right)^2 \hat{\mathbf{u}}^{\mathsf{T}} P_r \hat{\mathbf{u}}. \tag{17}$$

where P_r, P_v are the position and velocity sub-covariances.

V. Remarks

Equations (8)–(9) provide a compact and physically interpretable mapping from ephemeris/propagation errors to residual Doppler and timing advance (TA). These expressions make explicit how estimation errors in satellite state directly translate into impairments observed at the UE.

The numerical example demonstrates that modest update rates on the order of 1–5 seconds are typically sufficient for LEO satellites operating at microwave carriers. However, the rule scales with both carrier frequency and satellite acceleration; higher f_c or larger $(\mathbf{a}_{\text{sat}} \cdot \hat{\mathbf{u}})$ values require correspondingly faster update intervals.

Furthermore, the covariance-based formulations offer a systematic way to quantify statistical confidence levels. This enables the gNB to set conservative margins for pre- compensation, while also guiding the validity duration of SIB19 messages broadcast to the UEs. Such analysis provides both deterministic and stochastic insights into the robustness of real-time ephemeris update mechanisms in 5G NR-NTN operation.

VI. Results and Simulation

To validate the proposed framework, we simulated orbit propagation and Doppler prediction using TLE inputs with the SGP4 model. The user terminal was assumed to be fixed on the ground at Bangalore, India (12.97°N, 77.59°E). The carrier frequency was set at $f_c = 2$ GHz.

A. Assumptions and Model

We outline the key assumptions used in the analysis:

1) **Satellite and gNB States:** The true satellite state is denoted by position and velocity vectors $\mathbf{r}_{\text{sat}}(t)$ and $\mathbf{v}_{\text{sat}}(t)$. The gNB relies on an estimated state $\hat{\mathbf{r}}(t)$ and $\hat{\mathbf{v}}(t)$ computed at a reference epoch t_0 and used at time $t = t_0 + \Delta t$.

2) **Error Model (Ephemeris Staleness):** The dominant source of error is ephemeris staleness, modeled using first-order approximations:

$$\Delta \mathbf{v}(t) \approx \mathbf{a}_{\text{sat}}(t_0)\Delta t, \tag{18}$$

$$\Delta \mathbf{r}(t) \approx \mathbf{v}_{\text{sat}}(t_0)\Delta t. \tag{19}$$

where $\mathbf{a}_{\text{sat}}(t_0)$ is the satellite acceleration at epoch t_0. A worst-case projection is assumed, i.e., acceleration and velocity terms aligned with the line-of-sight (LOS), yielding conservative (upper-bound) residuals.

3) **Constants:** The following physical constants are used throughout the analysis:
   - $\mu = 3.986004418 \times 10^{14}\,\text{m}^3/\text{s}^2$
   - Earth radius: $R_e = 6371$ km
   - Speed of light: $c = 3 \times 10^8$ m/s

4) **Carrier Frequencies:** We consider
   - $f_c = 2$ GHz and
   - $f_c = 20$ GHz

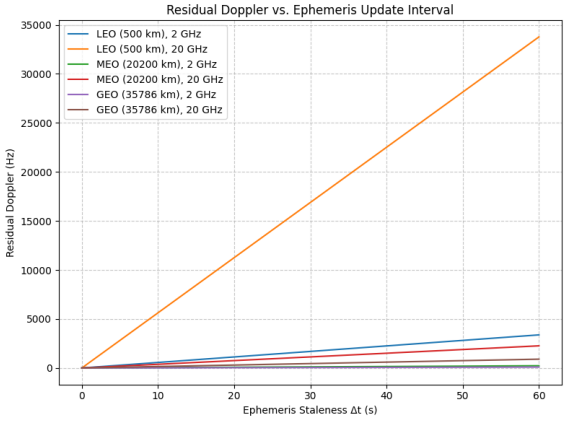

Fig. 2. Residual Doppler growth as a function of ephemeris update interval Δt for different orbital regimes (LEO, MEO, GEO) and carrier frequencies ($f_c = 2$ GHz and $f_c = 20$ GHz). LEO exhibits the steepest growth, while MEO and GEO remain more tolerant to update staleness.

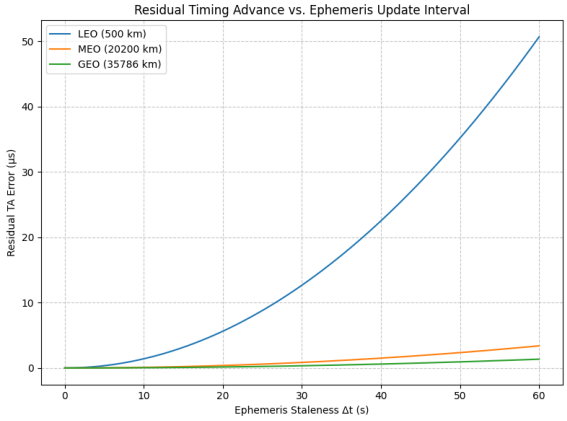

Fig. 3. Residual Timing Advance (TA) error versus ephemeris update interval for LEO, MEO, and GEO orbits. The TA error increases with ephemeris staleness due to growing position estimation errors. LEO satellites exhibit the highest sensitivity because of their larger orbital velocity, whereas MEO and GEO systems remain significantly more tolerant to update delays.

TABLE II
RECOMMENDED EPHEMERIS UPDATE INTERVALS FOR DIFFERENT ORBITS AND CARRIER FREQUENCIES

Orbit	**2 GHz**	**20 GHz**
LEO (500 km)	$\sim$5 s	$\sim$2 s
MEO (20,200 km)	$\sim$60 s	$\sim$20 s
GEO (35,786 km)	$>$ 60 s	$\sim$60 s

5) **Orbit Cases:** The following orbital regimes are considered:
   - **LEO:** Altitude $= 500$ km
   - **MEO:** Altitude $= 20{,}200$ km (typical GPS orbit)
   - **GEO:** Altitude $= 35{,}786$ km

B. Residual Doppler Growth with Ephemeris Update Interval

Fig. 2 shows how the residual Doppler varies with the ephemeris update interval Δt for LEO, MEO, and GEO orbits at carrier frequencies of $f_c = 2$ GHz and $f_c = 20$ GHz. The curves are obtained from the linearized expression in (18), using representative orbital accelerations for each altitude.

Several key observations can be made. For LEO, the residual Doppler rises very quickly, reaching a few hundred hertz within a few seconds at 2 GHz and several kilohertz at 20 GHz. This sensitivity makes frequent ephemeris updates—typically every 1–5 seconds—necessary for microwave and Ka-band operation.

MEO satellites show a much slower growth, with residuals in the tens to hundreds of hertz range even for delays approaching a minute at 2 GHz. GEO satellites are almost unaffected: even at 20 GHz, a 60-second delay leads to only a few hertz of residual Doppler, which is well within normal oscillator limits.

Finally, across all orbits, the linear dependence on carrier frequency is evident, with roughly a tenfold increase when moving from 2 GHz to 20 GHz. Overall, these results indicate that timely ephemeris updates are essential for maintaining accurate Doppler and TA compensation and for ensuring reliable UE synchronization in NTN systems.

C. Residual Timing Advance error with Ephemeris Update Interval

Fig. 3 illustrates the growth of residual Timing Advance (TA) error with increasing ephemeris update interval. Consistent with the first-order analytical framework developed in Section IV, the dominant position error is approximated as $\Delta r \approx v_{sat}\Delta t$, resulting in an approximately linear increase in residual TA error with ephemeris staleness. For LEO satellites, even a 10 s stale ephemeris can lead to non-negligible TA errors, while MEO and GEO systems remain considerably more tolerant due to their lower orbital dynamics.

TABLE III
RESIDUAL ERRORS FOR EPHEMERIS STALENESS $\Delta t = 10$ S.

Orbit	$\lvert v\rvert$ **(m/s)**	$\lvert a\rvert$ **(m/s^2)**	Δf **(2 GHz)**	Δf **(20 GHz)**	ΔTA **(ms)**
LEO (500 km)	7616.6	8.443	562.9 Hz	5628.7 Hz	0.508 ms
MEO (20,200 km)	5143.1	0.565	37.6 Hz	376.4 Hz	0.343 ms
GEO (35,786 km)	3074.9	0.224	15.0 Hz	150.0 Hz	0.205 ms

Table III shows the conservative upper-bound residuals for a 10-second ephemeris staleness. The residual Doppler is calculated using the acceleration-driven model $\Delta f_d \approx (f_c/c)\,|a|\,\Delta t$. The TA error is estimated by $\Delta TA \approx 2\,|v|\,\Delta t/c$ in the worst-case LOS alignment. For LEO, a 10-second stale ephemeris results in a residual Doppler of about ≈ 563 Hz at 2 GHz (around 5.6 kHz at 20 GHz) and a TA error of roughly 0.51 ms. The residuals for MEO and GEO are significantly smaller. This means that update frequencies can be much more relaxed for higher orbits. These figures support the recommended update intervals mentioned earlier: LEO needs frequent updates (on the order of seconds), especially at high carrier frequencies, while MEO and GEO can handle update intervals ranging from tens of seconds to minutes.

D. Monte Carlo Validation

To evaluate the robustness of the proposed analytical model beyond worst-case alignment assumptions, we conduct a Monte Carlo analysis over a large set of randomized scenarios.

Specifically, $N = 1000$ realizations are generated by randomly sampling user equipment (UE) locations within the satellite footprint. For each realization, the line-of-sight (LOS) projection angle is varied, and ephemeris errors in satellite position and velocity are modeled as zero-mean Gaussian random variables with covariance matrices $\mathbf{P}_r$ and $\mathbf{P}_v$, respectively.

The simulations assume a 500 km LEO orbit, a minimum UE elevation angle of 10°, Gaussian position and velocity uncertainties with standard deviations of 100 m and 0.1 m/s, respectively.

The residual Doppler and Timing Advance (TA) errors are computed using the linearized expressions derived in Section IV. This allows us to evaluate the statistical distribution of residual errors under realistic conditions, rather than relying solely on worst-case deterministic bounds.

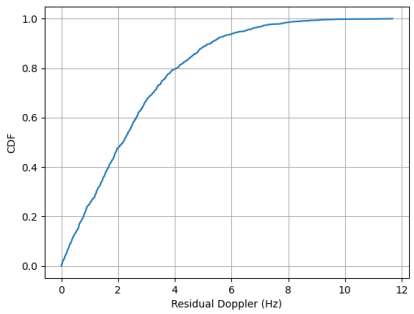

Fig. 4. CDF of residual Doppler error obtained from Monte Carlo simulations over random UE locations and LOS conditions. The majority of realizations remain below the analytical worst-case bound.

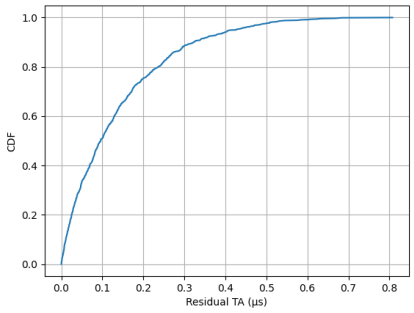

Fig. 5. CDF of residual Timing Advance (TA) error under stochastic ephemeris uncertainty. The results confirm the conservativeness of the analytical model.

Fig. 4 and Fig. 5 show the cumulative distribution functions (CDFs) of residual Doppler and TA errors, respectively. It is observed that more than 95% of realizations remain below the analytically predicted worst-case limits, confirming that the derived bounds are conservative.

These results demonstrate that the proposed analytical framework provides reliable design margins for practical NTN deployments, even under stochastic variations in UE location and ephemeris accuracy.

VII. Conclusion

This paper presented a quantitative framework for real-time ephemeris updates in 5G NR-NTN. It was motivated by the 3GPP requirement that OAM must provide ephemeris information to the gNB for Doppler and Timing Advance (TA) pre-compensation. We derived simple mathematical expressions that show how position and velocity estimation errors create residual Doppler and TA errors. We also gave formulas that show how the update interval depends on the orbit and the carrier frequency.

Simulation results for LEO, MEO, and GEO showed that update rates of 1–5 seconds are enough for LEO at 2 GHz to keep residual errors small. Higher carrier frequencies or longer update gaps cause errors to grow quickly. We also discussed practical trade-offs between update frequency, OAM/O1 signaling overhead, and SIB19 validity.

Overall, the results give useful design guidelines for NTN systems and help bridge the gap between 3GPP specifications and real implementation. Future work will extend this framework to multi-satellite constellations, beam hopping, and mobility scenarios.

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