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# The Relativistic Doppler Effect in Satellite Communications and Its Impact on Signal Accuracy

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***Abstract.*** Throughout the propagation process, high-speed satellite communication signals are significantly influenced by both special and general relativistic effects. These relativistic effects, including Doppler shifts, gravitational redshifts, and time dilation, cause frequency deviations and reception time errors, affecting communication accuracy and the positioning performance of navigation systems. In high-speed satellite links, relativistic effects directly contribute to carrier frequency offsets and timing errors, which can degrade synchronization and decoding performance. Therefore, accurate modeling and effective compensation of relativistic effects are required to reduce communication errors and boost system reliability. In particular, relativistic Doppler effects pose challenges for high-dynamic satellite links due to their direct influence on carrier frequency stability and timing synchronization. This paper reviews theoretical analyses, frequency shift assessments, and engineering correction methods for relativistic Doppler effects, focusing on their impact on signal synchronization and decoding accuracy. The results demonstrate that, although relativistic frequency shifts are small in magnitude, they cannot be neglected in high-precision communication and navigation systems; and effective correction methods, like satellite-side pre-compensation and ground-side post-correction, can mitigate these errors and improve system accuracy.

***Keywords:*** Satellite Communication, Relativistic Frequency Shift, Doppler Effect, Time Dilation, Signal Accuracy

## 1. Introduction

With the rapid development of Global Navigation Satellite Systems (GNSS), low-Earth-orbit (LEO) broadband constellations like Starlink, and deep-space communication networks, modern satellite communication systems require enhanced frequency stability and time synchronization accuracy. In particular, tasks such as high-precision navigation, inter-satellite links, and deep-space tracking and control now demand nanosecond-level or even higher precision. In this context, relativistic effects caused by satellite motion and gravitational field variations introduce frequency shifts and timing errors into satellite communication systems. Previous studies showed that special relativistic time dilation reduces satellite clock frequencies, whereas the general relativistic gravitational frequency shift increases them. These effects introduce measurable frequency deviations in satellite signals, impacting synchronization, carrier tracking, demodulation, and ranging/positioning accuracy [1]. To mitigate these effects, current systems like GPS, BeiDou, and Galileo have implemented relativistic

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frequency shift compensation via onboard clock pre-calibration and real-time ground corrections. However, with the development of low-orbit megaconstellations, high-frequency communication links, and onboard optical clocks, the limitations of existing compensation methods in adapting to dynamic environments and achieving ultra-high precision have become increasingly apparent. This paper explores relativistic frequency shifts in high-speed satellite signals, analyzing the mechanisms of time dilation and gravitational frequency shifts and their influences on communication signal accuracy. Furthermore, the effects of these shifts are evaluated, and the implementation approaches and applicable conditions of existing correction methods are summarized.

## 2. Principles of the relativistic effects on high-speed satellite signals

### 2.1. Time expansion effect

Under special relativity, a satellite clock moving at high velocity runs slower than a stationary ground-based clock, a phenomenon known as time dilation. Accordingly, the relationship between the time interval measured by the satellite and that measured by the stationary ground clock is given by:

$$\Delta t = \frac{\Delta t}{\sqrt{1-\frac{v^2}{c^2}}} \tag{1}$$

where v is the satellite's velocity relative to the ground, and c is the speed of light. As the satellite's motion speed increases, its clock rate decreases relative to ground clocks, resulting in a longer clock period and a lower oscillation frequency. Thus, the relationship between the actual frequency of the signal transmitted by the satellite and its nominal frequency is expressed as:

$$f \approx f_0\left(1 - \frac{v^2}{2c^2}\right) \tag{2}$$

The time dilation effect causes a negative frequency shift in satellite signals, whose magnitude is proportional to the square of the satellites velocity and is particularly pronounced in high-speed orbits. For typical navigation satellites, the resulting relative frequency shift is on the order of $10^{-10}$, which is a critical factor to consider in satellite clock frequency correction [2].

### 2.2. Gravitational shift effect

According to general relativity, the gravitational potential at the satellite's location is higher than that at the Earth's surface, causing the satellite clock to run faster than a ground-based clock. Under weak gravitational field conditions, the relative change in clock frequency and the gravitational potential difference $\Delta\Phi$ satisfy the following relation:

$$\frac{\Delta f}{f} = \frac{\Delta \Phi}{c^2} \tag{3}$$

where $c$ denotes the speed of light. The Earths gravitational field is approximately spherical and symmetric; as satellites move farther from the Earths center, their gravitational potential energy decreases, causing their clock oscillation frequency to increase accordingly. Consequently, satellite signals exhibit a positive frequency shift, which contrasts with the time dilation effect predicted by special relativity. Taking a typical medium-orbit satellite (such as a GPS satellite) as an example, the

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magnitude of the gravitational frequency shift is approximately $+5\times10-^{10}$. This corresponds to an increase of approximately 0.8 Hz in the L-band signal, while time dilation along the same orbit induces a negative frequency shift of about −0.1 Hz. It is evident that gravitational frequency shifts dominate satellite signals and constitute the primary cause of frequency elevation [1].

### 2.3. Frequency offset pattern

The actual frequency shift of satellite signals is determined jointly by the time dilation effect and the gravitational frequency shift effect, with its total relative frequency shift expressed as:

$$\frac{\Delta f}{f} = \frac{GM}{c^2}\left(\frac{1}{R_{\text{Earth}}} - \frac{1}{R_{\text{satellite}}}\right) - \frac{v^2}{2c^2} \tag{4}$$

where the term associated with the gravitational potential difference refers to the general relativistic gravitational frequency shift, whereas the velocity-dependent term represents the special relativistic time dilation contribution. As orbital altitude increases, the orbital velocity of the satellite gradually decreases while the gravitational potential difference increases, leading to variations in the relative contributions of the two relativistic effects. LEO satellites are mainly influenced by time dilation, resulting in a negative net frequency shift. With increasing altitude, the gravitational frequency shift gradually dominates, hence yielding a positive net shift. For medium- and high-Earth-orbit satellites, such as geostationary orbit (GEO) satellites, gravitational frequency shift dominates the frequency deviation. Thus, relativistic frequency shifts in satellite signals exhibit distinct orbital dependence, with their magnitude and direction determined jointly by orbital altitude and orbital velocity. This indicates that relativistic frequency shifts are not constant but closely related to the satellites orbital state. Different orbital types require tailored frequency compensation strategies to ensure accuracy in clock synchronization, carrier tracking, and ranging/positioning [1].

## 3. The impact of relativistic frequency shift on the accuracy of communication signals

### 3.1. Signal frequency shift

Frequency shifts induced by relativistic effects constitute systematic deviations rather than random noise; thus, they do not vanish when averaged over time but persist and accumulate over operational duration. Satellite motion and the gravitational potential difference between the satellite and Earth shift the onboard clock frequency relative to the ground reference, creating a fixed offset between the received signal frequency and the nominal transmission frequency.

The resulting frequency discrepancy is primarily determined by the satellite's orbital altitude and velocity [3]. Though relativistic frequency shifts are typically at the sub-Hertz to several-Hertz level, their effects persist over time and accumulate. In high-precision measurement systems, even minute frequency shifts gradually translate into observable phase and timing errors. For instance, early test results from the European Galileo Navigation System demonstrated that uncompensated relativistic frequency shifts introduce centimeter-level systematic errors in carrier phase measurements, thereby reducing the accuracy of precise point positioning (PPP) [4]. Moreover, relativistic frequency shifts directly affect receiver frequency estimation, introducing persistent deviations between the received signal frequency and its theoretical value. Without adequate compensation, these errors degrade carrier tracking precision and time synchronization accuracy. Therefore, relativistic frequency shifts introduce non-negligible errors in high-precision satellite communication and navigation systems.

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### 3.2. Signal synchronization and decoding

The carrier frequency offsets induced by relativistic frequency shifts can degrade synchronization and demodulation performance in communication systems. Since digital receivers require precise restoration of carrier frequency and symbol clock signals, persistent frequency offset introduces steady-state tracking errors in phase-locked loops (PLLs), thereby reducing carrier synchronization accuracy and compromising demodulation performance. The effects vary across system types: in OFDM systems, frequency offset compromises subcarrier orthogonality, leading to inter-subcarrier interference (ICI); whereas in spread spectrum communication systems (e.g., CDMA or satellite navigation signals), it weakens the correlation between local codes and received codes, degrading signal acquisition and tracking performance. In scenarios requiring high-frequency synchronization, this can prolong synchronization time or even cause tracking loss. Besides, sensitivity to frequency offsets increases with modulation order. High-order modulation schemes like 64QAM have smaller constellation spacing, making them more susceptible to frequency errors and increasing the bit error rate even under small frequency shifts [5]. Thus, high-spectrum-efficiency satellite communication systems must implement effective compensation for relativistic frequency shift to ensure carrier synchronization accuracy and optimal signal demodulation performance.

### 3.3. The magnitude of frequency shift and the required corrections

Under different orbital conditions, the magnitude of relativistic frequency shifts varies significantly, but their order of magnitude is generally at the level of $10^{-10}$. And the relative contributions of gravitational frequency shift and time dilation vary across different orbits, resulting in distinct net frequency shifts for LEO, MEO, and GEO satellites. The results are summarized in Table 1.

Table 1. Order of magnitude of relativistic frequency shifts for typical satellite orbits

| Classification of Track | Altitude (km) | Speed (km/s) | Gravitational Term $10^{-10}$ | Speed Item $10^{-10}$ | Net Frequency Shift $10^{-10}$ |
|---|---|---|---|---|---|
| Low-Earth Orbit (LEO) | 500 | 7.62 | +1.1 | -3.3 | -2.2 |
| Low-Earth Orbit (LEO) | 1500 | 7.12 | +2.0 | -2.8 | -0.8 |
| Medium-Earth Orbit (MEO) | 20200 | 3.87 | +5.3 | -0.83 | +4.47 |
| Geostationary Orbit (GEO) | 35786 | 3.07 | +6.8 | -0.53 | +6.27 |

Although the net relative frequency shifts vary across satellites in different orbits, they all remain on the order of $10^{-10}$. For conventional communication systems, such errors may be negligible. However, in high-precision applications such as navigation, inter-satellite links, and satellite laser communications, where frequency stability requirements typically reach $10^{-11}$ or higher, relativistic frequency shifts can approach the allowable error limits. Therefore, without proper compensation, it constitutes a significant error source that undermines the accuracy of both frequency and time synchronization. Furthermore, as the carrier frequency increases, the same relative frequency shift translates into a larger absolute frequency deviation, thereby amplifying its impact. Consequently,

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the relativistic frequency shift has become a fundamental error term that must be accounted for in modern satellite communication and navigation systems. Mitigation measures, such as frequency pre-compensation and clock steering/correction, are essential to meet the stringent requirements for high-precision frequency and time synchronization.

## 4. Methods for correcting relativistic frequency shifts in satellite communications

### 4.1. Satellite end frequency compensation

In practical satellite systems, satellite frequency compensation has been widely adopted as a method for correcting relativistic frequency shifts. Its fundamental approach involves calculating the net relative frequency shift based on predetermined orbital parameters before satellite launch, followed by applying a reverse pre-bias to the onboard clock. This ensures that during orbital operation, the satellites actual output frequency approaches the designed nominal value despite the effects of gravitational frequency shifts and time dilation [6]. For example, the net relative frequency shift of MEO GPS satellites is approximately $4.47\times 10^{-10}$ . To compensate for this shift, the onboard atomic clock reference frequency is adjusted to about 10.2299999954 MHz before launch, rather than the nominal 10.23 MHz. After the satellite enters orbit, relativistic effects cause the clock frequency to increase, thus compensating for the preset frequency offset and ultimately achieving the designed operating frequency [1]. This approach offers reliable and stable compensation with relatively low implementation complexity, and has been employed by major global navigation satellite systems, including GPS, BeiDou, GLONASS, and Galileo [7]. In particular, BeiDou-3 further integrates onboard clock offset correction with ground-based update mechanisms in addition to frequency pre-offsetting, thus improving time synchronization accuracy. It should be noted that the pre-offset compensation relies on accurate and relatively stable orbital parameters. During orbital maneuvers, orbit variations, or long-term drift, the actual relativistic frequency shift may differ from the preset value. Therefore, fixed pre-offset compensation alone cannot maintain long-term accuracy, and dynamic correction based on ground measurement and control systems is required.

### 4.2. Ground-side frequency correction

When satellite-side pre-compensation becomes insufficient, ground-based frequency correction can be adopted. This method uses satellite orbit information and relativistic frequency shift models to estimate the instantaneous frequency offset and performs dynamic compensation at the receiver to mitigate deviations induced by relativistic effects. Compared with satellite-side pre-compensation, ground-based correction provides better adaptability to dynamic conditions by enabling real-time updates for orbital maneuvers and prediction errors. It is well suited for low-orbit constellations with significant parameter variations and deep-space communication scenarios. This method has been used in high-precision navigation receivers and deep-space tracking systems. For example, GNSS processing software such as PRIDE PPP-AR corrects residual relativistic terms in satellite clock errors during data processing [8]. NASA's Jet Propulsion Laboratory (JPL) GipsyX/RTGx software integrates precise ephemerides with relativistic models to enable real-time corrections in global differential GPS (GDGPS) systems, improving velocity and range measurement accuracy [9]. The effectiveness of this compensation depends on the precision of orbital parameters and update frequency; increased orbit prediction errors or simultaneous processing of multiple satellites may compromise both accuracy and real-time performance. Thus, practical systems typically combine

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these approaches with additional precision mechanisms, such as orbit determination and frequency tracking algorithms, to improve correction accuracy.

### 4.3. Modifications and limitations

In high-precision satellite applications, relativistic frequency shift correction is widely employed to maintain the accuracy of navigation, communication, and deep-space tracking systems. Through methods like onboard clock pre-biasing, navigation message parameter adjustments, and real-time receiver compensation, global navigation satellite systems such as GPS, BeiDou, and Galileo have achieved nanosecond-level time synchronization accuracy. In satellite laser communications and deep-space communications, relativistic corrections reduce frequency and timing errors, improving ranging, velocity estimation, and communication stability.

However, existing correction methods are constrained by orbit prediction errors, environmental effects, and model uncertainties. As large-scale LEO constellations grow and communication bands shift toward higher frequencies, achieving accurate frequency synchronization and time reference stability becomes more difficult for conventional static and semi-static compensation methods. With the advancement of space-borne optical clocks and quantum frequency reference technologies, the frequency stability of space time-frequency systems is expected to reach the $10^{-18}$ level. Under such precision requirements, small relativistic effects can noticeably influence system performance [10]. Therefore, high-precision space time-frequency references require the integration of precise orbit determination, real-time gravitational potential models, and dynamic correction algorithms to achieve real-time modeling and high-accuracy maintenance.

## 5. Conclusion

This study investigates relativistic effects in high-speed satellite signals and their influence on communication and navigation systems. The findings indicate that time dilation and gravitational frequency shifts jointly produce measurable frequency deviations, which further degrade carrier synchronization, signal demodulation, and ranging accuracy. By employing pre-bias adjustments at the satellite end combined with dynamic corrections at ground stations, most relativistic frequency shifts can be effectively compensated, enabling high-precision time synchronization and frequency stability. However, the analysis mainly relies on typical orbital parameters and existing navigation system models, lacking sufficient consideration for practical dynamic environments required by low-orbit mega constellations, high-frequency inter-satellite links, and future optical clock systems demanding even higher precision. Future research should integrate high-precision onboard clocks, real-time gravitational potential models, and dynamic frequency correction algorithms to enable accurate relativistic compensation for large-scale satellite constellations and deep-space missions, supporting next-generation satellite communication and navigation systems.

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