

A novel method for ionospheric monitoring using stellar occultation

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Key Points:

- Feasibility study of ionospheric stellar occultation detection technology.
- Ionospheric stellar occultation forward and inversion model construction and simulation accuracy analysis.
- Inversion simulation and accuracy analysis of ionospheric stellar occultation.

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Abstract: The ionosphere is an important region that directly affects human activities. Existing ionospheric space-based detections are limited by airspace coverage, while ground-based observations are constrained by geographic environments, making observational deployment in oceans and deserts impractical. Direct measurements via satellite are restricted by orbital paths, and cannot fully cover the ionosphere. While Global Positioning System (GPS) ionospheric occultation enables global monitoring of the ionosphere, it relies on the availability of navigation satellites. Stellar occultation, using stars as light sources for the detection of planetary atmospheres and the advantages of GPS radio occultation, allows for observation constellations to achieve comprehensive global monitoring. In this study, we validate the feasibility of the ionospheric stellar occultation technique. First, 141 ultraviolet sources were selected based on the spectral absorption characteristics of 303.31 Å and signal-to-noise ratio requirements of the observation spectrum. Second, the 24-hour distribution of ionospheric occultation events was forecasted through satellite orbits and stellar positions. Third, a forward projection model was built based on the predicted occultation events, and the International Reference Ionosphere (IRI) model was employed to simulate the transmission of ionospheric occultation observations. Finally, the simulated transmittance was used as an input to retrieve the ionospheric electron density profiles using the onion-peeling inversion method, with errors calculated against the IRI model. Results show that stellar occultation provides five times more events than GPS radio occultation, under identical orbital conditions. The inversion error at the electron density peak remains below 2%, with even smaller errors at heights below the peak. These results confirm the feasibility and practicability of the ionospheric stellar occultation technique, offering a method for a deeper understanding of ionospheric physical processes, the development of ionospheric space weather forecasting, as well as long-term, stable, and global observations of the ionosphere.

Keywords: stellar occultation; ultraviolet; ionospheric F-region; forward modeling; inversion

1. Introduction

Ionospheric radio occultation techniques have become widely recognized as a reliable and effective tool for ionospheric monitoring on a global scale (Rocken et al., 2000; Gorbunov et al., 2000; Ao et al., 2003; Martín-Neira, 2016; Wang JY et al., 2018; Schreiner et al., 2020; Tang L et al., 2023; Du JH et al., 2025), enabling retrieval of the total electron content (TEC) and electron density profile for meteorological and space weather research. However, existing ionospheric monitoring methods still have limitations. Ionosondes, for example, can only provide observations over land-based stations, and are unable to cover oceans and remote areas.

Global Navigation Satellite System (GNSS) radio occultation, capable of global monitoring, relies on the availability and geometric distribution of navigation satellites, which limits its spatiotemporal resolution and the number of occultation events. Satellite in-situ measurements are restricted by orbital paths and cannot fully cover the ionosphere (He J et al., 2022; Basciftci and Bulbul, 2023; Ozdemir et al., 2024), hence, it is imperative to develop a variety of ionospheric monitoring methods. The ionospheric emission of the far ultraviolet (FUV) wavelength band, unaffected by the Earth's complex background atmosphere, is an important source of information on physico-chemical and dynamical processes in the Earth's ionosphere (Strickland et al., 1983; Meier, 1991; Wang YM et al., 2008; Peng SF et al., 2012). In the ionospheric F-region (140–500 km), the concentration of O⁺ accounts for about 95% of the total ion concentration, which is considered approximately equivalent to the total plasma density in that altitude range (Adebesin and Adeniyi, 2018; Wang DX, 2020). Therefore, it has

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been used as an important tracer for monitoring the Earth's ionosphere. Current optical methods predominantly rely on airglow radiation (Chandra et al., 1975; Ajello and Shemansky, 1985), which enables the retrieval of key physical parameters such as the TEC and the peak electron density ($NmF2$) in the nighttime and daytime ionosphere. However, airglow-based approaches are inherently constrained by their dependence on specific emission conditions, rendering them unsuitable for continuous all-weather observations.

To address the limitations of current ionospheric monitoring methods, this study proposes a novel application of stellar occultation for monitoring the Earth's F-region ionosphere. Stellar occultation is an internationally established technique for analyzing neutral particle compositions in planetary atmospheres (Bertaux et al., 2007; Forget et al., 2009). It also has the advantages of global ionospheric monitoring, high vertical resolution, and eliminates the need for absolute calibration (Kyrölä et al., 2004, 2010). Additionally, in the process of monitoring the ionosphere using this technology, while airglow typically acts as a background interference, its low radiant intensity above 200 km allows uninterrupted global full-time ionospheric monitoring using a single characteristic spectral line. Furthermore, compared with GNSS radio occultation technology, stellar occultation not only has the advantages of high vertical resolution and all-weather observation of radio occultation, but also offers a large number of observational light sources, and a wide distribution, with a certain number of target stars observable in each band. At present, GNSS radio occultation can only use existing navigation satellites as signal sources, which limits the number and coverage of occultation observations to some extent.

By extending the stellar occultation technique to ionospheric studies, critical parameters such as neutral species concentrations (e.g., O, NOx), ion densities, and thermospheric temperatures above 200 km can be retrieved (Wang YM et al., 2008; Peng SF et al., 2012; Wang DX, 2020). These capabilities are pivotal for real-time space environment monitoring and advancing ionospheric physics research. Notably, while solar occultation (using the Sun as a source) benefits from high signal intensity, its limited daily occultation events and inherent positional constraints necessitate the integration of additional stellar sources to enhance data accuracy and temporal resolution.

2. Method

2.1 Beer–Bouguer–Lambert Law

When light propagates in the Earth's atmosphere, it experiences absorption and scattering due to interactions with atmospheric molecules and aerosol particles, resulting in attenuation of the light intensity:

$$\frac{dI_\lambda}{k_\lambda \rho ds} = -I_\lambda, \quad (1)$$

where I_λ is the radiation intensity, ρ is the number density of atmospheric molecules, ds is the thickness in the propagation direction, and k_λ is the mass extinction cross-section, equal to the sum of the mass absorption and mass scattering cross-sections. Suppose that the incident intensity at $s = 0$ is $I_\lambda(0)$, and the exit

intensity after passing through the path s_1 is

$$I_\lambda(s_1) = I_\lambda(0) \exp\left(-\int_0^{s_1} k_\lambda \rho ds\right). \quad (2)$$

Considering that the uniform medium condition k_λ is independent of the distance, and the transmission path u is defined as

$$u = \int_0^{s_1} ds. \quad (3)$$

Then, the emission intensity can be transformed into the following form:

$$I_\lambda(s_1) = I_\lambda(0) \exp(-k_\lambda \rho u), \quad (4)$$

where k_λ is the mass extinction cross-section, and u is the transmission path. The above formula is the Beer–Bouguer–Lambert law. That is, when the radiation intensity passes through a uniform extinction medium, it will gradually weaken according to the law of exponential function. Based on the above formula, the monochromatic transmittance can be defined as

$$T_\lambda = \frac{I_\lambda(s_1)}{I_\lambda(0)} = \exp(-k_\lambda \rho u). \quad (5)$$

For a medium without scattering, the monochromatic absorptivity is defined as

$$A_\lambda = 1 - T_\lambda = 1 - \exp(-k_\lambda \rho u). \quad (6)$$

Based on this physical principle, the occultation detector is employed to observe stellar transits across Earth's ionospheric boundary from the satellite's orbital perspective. Through analysis of stellar signal attenuation patterns recorded during these ingress/egress events, the spectral absorption features induced by trace constituents in the ionosphere are quantitatively characterized. For the retrieval of specific ionospheric component densities, we employ three physical quantities (T_λ , k_λ and u) integrated with the onion-peeling method to derive the density of a specific ionospheric component.

2.2 Principle of Ionospheric Monitoring Using Stellar Occultation

The absorption mechanism of O^+ ions in the extreme ultraviolet (EUV) band is fundamentally different from radio-wave absorption in the ionosphere. Radio-wave absorption is governed by free-electron collisions with neutral particles and ions (inverse bremsstrahlung), with absorption magnitude depending on electron density and wave frequency (Rishbeth and Garriott, 1969). In contrast, the absorption mechanism of O^+ ions in the extreme ultraviolet (EUV) band is governed by electron energy-level transitions and ionization processes, with absorption spectral lines directly tied to inter-level energy differences. Specifically, selective absorption occurs when EUV radiation matches the energy gap of inner-shell electron transitions in O^+ . At 30.331 nm, the photon energy calculated via $E = hc/\lambda$ (where h and c denote the Planck constant and speed of light, respectively) is approximately 40.9 eV, aligning precisely with the $2p \rightarrow 3s$ transition in O^+ . The ground-state electronic configuration of O^+ ($1s^2 2s^2 2p^3$) facilitates this inner-shell transition, which exhibits a high strength, and is quantum-mechanically allowed due to compliance with dipole selection rules ($\Delta l = \pm 1$). This results in a significantly enhanced absorption

cross-section at 30.331 nm compared to neighboring wavelengths, making it a critical diagnostic feature for detecting O^+ density gradients in ionospheric monitoring via stellar occultation. As illustrated in Figure 1, stellar occultation ionospheric detection employs geometric occultation events between spacecraft-observed stars and the ionospheric limb to establish tomographic reconstruction of ionospheric parameters. The stellar occultation method begins when the satellite observes a star as it sets (occults) behind Earth's limb. Data collection starts with the direct, non-occulted signal (ray S_0) and continues through the occultation event as the star's light passes through the ionosphere (ray S). The process is unidirectional, with the satellite tracking the star's descent relative to Earth's horizon. The time-series data of the star's signal attenuation are processed to derive ionospheric electron density.

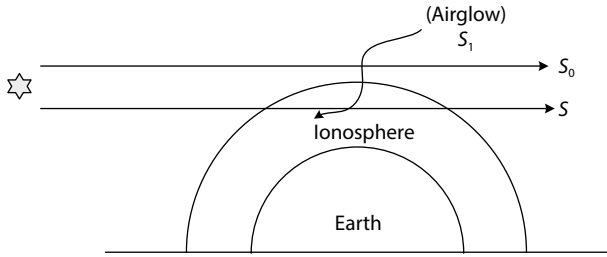


Figure 1. Schematic diagram of stellar occultation ionospheric detection.

During the occultation, as the line-of-sight tangent height progressively decreases, the received stellar spectra S vary accordingly, while the reference spectrum S_0 is obtained outside the ionosphere without absorption. However, the measured signal is also contaminated by background airglow emissions S_1 originating from the upper atmosphere. This spontaneous radiation phenomenon manifests as intensity enhancement that obscures absorption features, necessitating rigorous correction through airglow interference modeling. The radiation intensity relationship governing this compensation process is expressed by Equation (7):

$$T = \frac{S - S_1}{S_0} = e^{-\rho \sigma l}, \quad (7)$$

where T represents the spectral observation transmittance, ρ is the density profile of O^+ , σ is the absorption cross-section of ion, and l corresponds to the optical path length through the ionosphere from the source to the receiver. The density profile of O^+ is derived via Equation (8). Given that O^+ accounts for 95% of the electron concentration in the F-region, the TEC value can be calculated using Equation (9):

$$\rho = \frac{-\ln T}{\sigma l}, \quad (8)$$

$$\text{TEC} = \rho \cdot l. \quad (9)$$

The proposed methodology enables continuous monitoring of F-region ionospheric electron density through the aforementioned physical principles. Usually, the stellar signal source is very far away from the receiver, and the distance is calculated in light years, so it can be considered a point source. However, this config-

uration inherently results in attenuated signal-to-noise ratios (SNR), necessitating systematic correction for stray light contamination during signal acquisition. In practical implementations, background interpolation techniques are employed to mitigate these photonic disturbances. To analyze these radiative interference effects, Figure 2 illustrates the distribution of the global atmospheric airglow derived from the previous result of Solomon (2017).

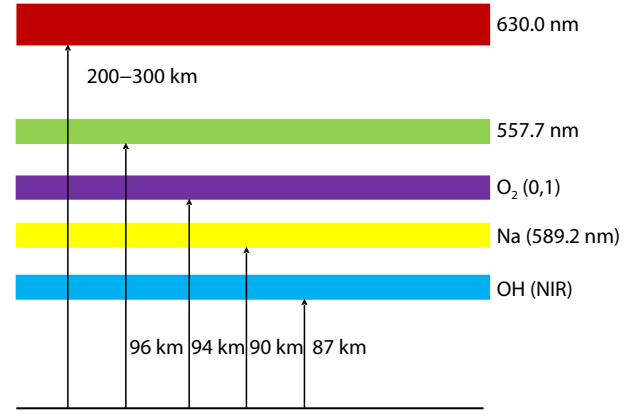


Figure 2. Distribution of typical atmospheric airglow.

It is worth noting that the colored bars in Figure 2 have no special meaning, and only represent different types of airglow distinguished by different colors. As illustrated, dominant airglow emissions are predominantly confined to altitudes below 100 km, and emissions above 200 km primarily occupy the near-infrared wavelength band. These emissions prove negligible for the current analysis, thereby validating the observational strategy for ionospheric monitoring through selective spectral filtering.

3. Analysis of the Experimental Results

Given the current absence of operational spaceborne instruments implementing stellar occultation techniques for terrestrial ionospheric monitoring, and the consequential lack of empirical datasets, this study establishes a comprehensive simulation framework to validate the methodology's feasibility. It mainly comprises five methodologically sequential components: (1) ultra-violet reference star selection based on spectral luminosity criteria; (2) ionospheric occultation event prediction; (3) forward modeling of stellar occultation processes; (4) development of an inversion algorithm for stellar ionospheric occultation; and (5) systematic validation.

3.1 UV Star Source Screening

The identification of all-sky UV sources follows established criteria requiring spectral signal-to-noise ratios exceeding 100 dB and instrumental efficiency greater than 0.1107, as outlined in previous research (Sun MC et al., 2019). The continuous spectrum emitted by a star with flux F_λ per unit wavelength and apparent brightness F can be defined as an integral over all wavelength intervals (Zhu QL et al., 2022), as shown in Equation (10):

$$F \equiv \int_0^\infty F_\lambda(\lambda) d\lambda. \quad (10)$$

In stellar photometry, the apparent brightness of a star is conventionally quantified through the magnitude, where brighter stars have numerically smaller magnitudes. Based on the quantitative relationship between the apparent magnitude and apparent brightness, the mathematical formulation of this relationship is presented in Equation (11), which defines the range of apparent magnitudes of a star source:

$$m_1 - m_2 = -2.5 \log_{10}(F_1/F_2). \quad (11)$$

This photometric relationship demonstrates that when Star 1 exhibits approximately 2.5 times higher luminous flux than Star 2 ($\Delta m \approx 1.0$), the magnitude system effectively operates as a base-10 logarithmic scale. Specifically, a differential magnitude of 0.1 corresponds to a 10% flux variation, reflecting the fundamental scaling law of stellar photometry. The stellar catalog used in this study is the HIPPARCOS catalog, which provides high-precision astrometric data. Through systematic photometric analysis under observational constraints (SNR > 100 dB), we identified 141 qualified stellar sources with apparent magnitudes ranging from -1.46 to 4 . Among them, stars brighter than magnitude 0 (i.e., with negative magnitudes) were naturally included, as their higher flux further improves the SNR. Their spatial distribution in the celestial

Sphere (Aitoff Projection) is visualized in Figure 3, where red five-pointed stars denote the positions of the target stars.

The key parameters of some stellar sources, including their coordinates, magnitudes, and flux values, are presented in Table 1.

3.2 Forecasting the Distribution of Ionospheric Occultation Events

The main purpose of this section is to describe the forecasting of stellar occultation ionospheric events, to simulate and analyze daily observations as well as the distribution of events, and to provide orbital data for the simulation of observational data. On the one hand, it is necessary to calculate the durations in order to estimate the storage space that may be required. On the other hand, it is necessary to validate the results of the stellar occultation ionospheric event distributions against the radio occultations (Du XY et al., 2007; Sun LG et al., 2017). To maximize acquisition of high-quality ionospheric occultation events, precise monitoring of real-time kinematic parameters (elevation angle and azimuthal variation) in star-satellite geometry is essential. Furthermore, under the local spherical symmetry approximation employed in the data inversion process, we quantify the occultation tangent

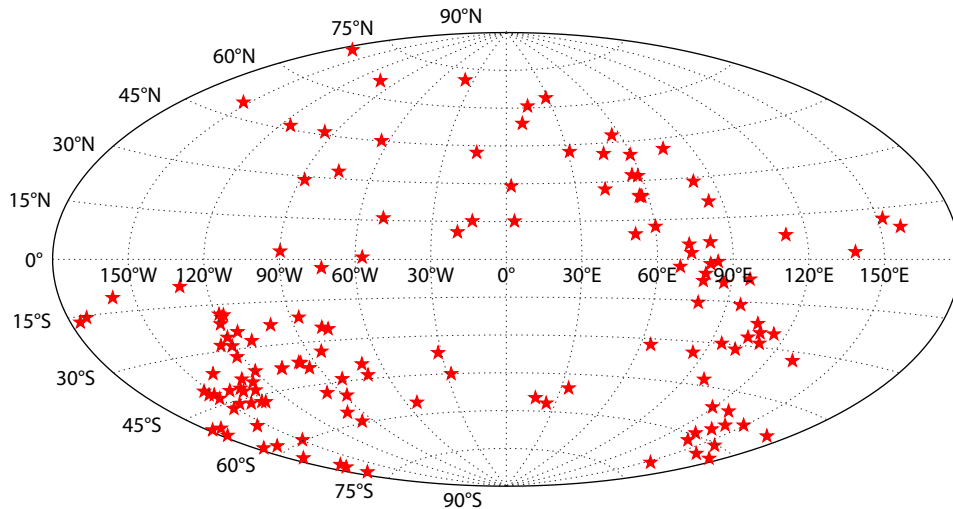


Figure 3. Ultraviolet target source distribution.

Table 1. List of stellar source examples.

Star name	Right ascension (°)	Declination (°)	Spectral type	Apparent magnitude
α , 21 And	2.097713	29.09043889	B9p	2.073
γ , 88 Peg	3.3094468	15.18355556	B2IV	2.834
ζ , 17 Cas	9.2448222	53.89692222	B2IV	3.67
γ , 27 Cas	14.178605	60.71671944	B0IV: evar	2.3
ζ , ζ Phe	17.096789	-54.75420556	B6V+...	3.99
α , α Eri	24.4299784	-56.76328333	B3Vp	0.453
ϵ , 45 Cas	28.5995862	63.67007778	B2pvar	3.368
γ 2, γ 1 And	30.9766446	42.32971944	B8V	2.26
ϕ , ϕ Eri	34.1285326	-50.48776667	B8IV-V	3.549
41, 41 Ari	42.4979218	27.26050278	B8Vn	3.612

point drift magnitude, a critical parameter inversely correlated with inversion accuracy, as increased horizontal drift distance (Δd) induces greater deviation from the fundamental assumption of horizontal ionospheric homogeneity. The simulation conditions are as follows:

(1) Satellite orbit root number

The orbital simulation framework in this study employs the epoch-specific orbital elements of the Challenging Minisatellite Payload (CHAMP) satellite (Wu DL et al., 2005) for August 1, 2008, when it was in a near-polar orbit with an initial altitude of ~ 454 km, an inclination of 87.3° , and a period of ~ 93.6 min. These parameters were chosen for two validation purposes: (1) to establish a benchmark for ionospheric retrieval algorithm verification, and (2) to enable direct cross-comparison with contemporaneous GPS radio occultation datasets (Wu XC, 2008). This strategic parameter selection ensures methodological consistency, as both the stellar occultation simulations and GPS radio occultation validation processes utilize identical CHAMP-derived ephemeris characteristics.

(2) UV source coordinates

(3) The height of the tangent point was 100–500 km

(4) The tangent point was located on the satellite–star line

The simulation results are presented in Figure 4, with comparative analysis performed against radio ionospheric occultation data (Rishbeth and Garriott, 1969).

The dataset comprises 4414 ionospheric stellar occultation events, including 2049 ascending occultations. Spatially, the events exhibit a latitudinal dependence with higher occurrence rates at low latitudes, and relatively fewer events at mid-latitudes and polar regions, while maintaining uniform longitudinal distribu-

tion. The elevation angle of occultation events is mainly distributed around 30° , which corresponds to the lateral occultation and belongs to the ascending occultation. Another elevation angle of 0° – 5° corresponds to the normal occultation and belongs to the descending occultation. Compared with the ionospheric radio occultation events (the 24-hour simulation resulted in 862 events with 29 signal sources), there were five times as many stellar occultation events, demonstrating the technique's enhanced daily observational capacity for ionospheric monitoring.

For comparative analysis with ionospheric radio occultation, side occultations were defined as those with azimuths between 45° – 135° and 225° – 315° , determined by averaging the initial and final azimuth values. The side occultations occurred 1,153 times, accounting for 26.12% of the total number of occultations, a proportion consistent with that observed in ionospheric radio occultation.

The comparative characteristics between normal and side occultations are presented in Table 2, with corresponding radio simulation results detailed in Table 3 (Wu XC, 2008). The analysis reveals that normal ionospheric occultations exhibit an average duration of 9 minutes, consistent with radio occultation measurements. However, significant differences emerge in the horizontal drift distances of the tangent points between the two techniques.

Figure 5 presents the duration (500–900 s) and horizontal drift distance (0–4500 km) of the normal occultations, compared to 500–860 s and 50–2000 km for ionospheric radio occultations. Analysis reveals that minimum occultation duration and the tangent horizontal drift occur at azimuth angles of 0° , 180° , and 360° , with values increasing toward maximum near 90° and 270° . This spatial dependence originates from the target source's deviation from the LEO orbital plane, as illustrated in Figure 6 (E1 and E2 denote elevation angles; A indicates azimuth angle; the arrow

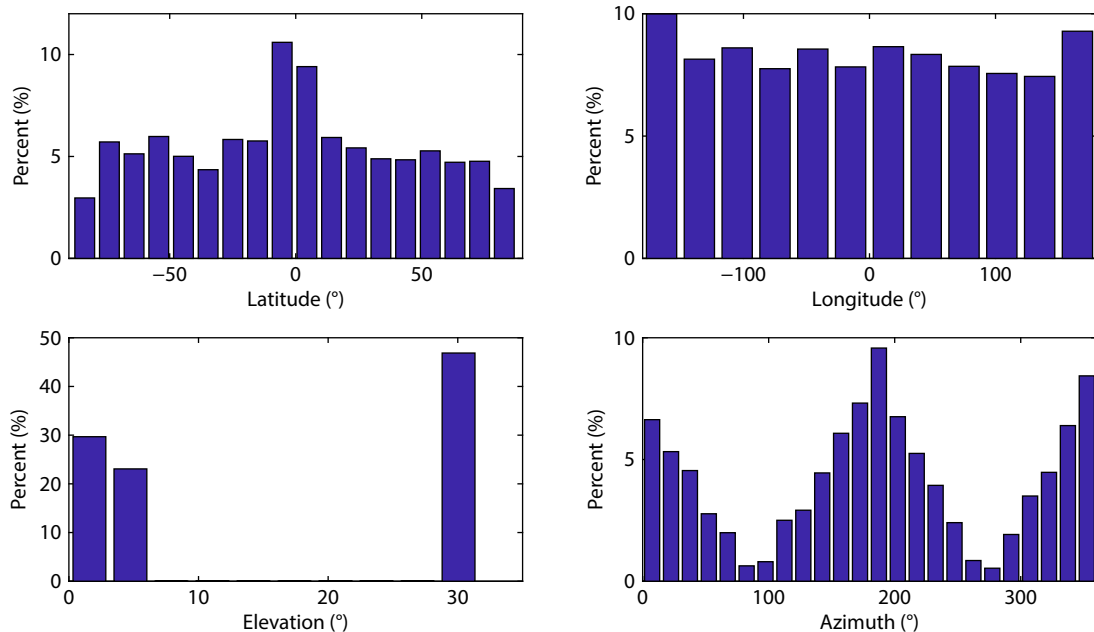


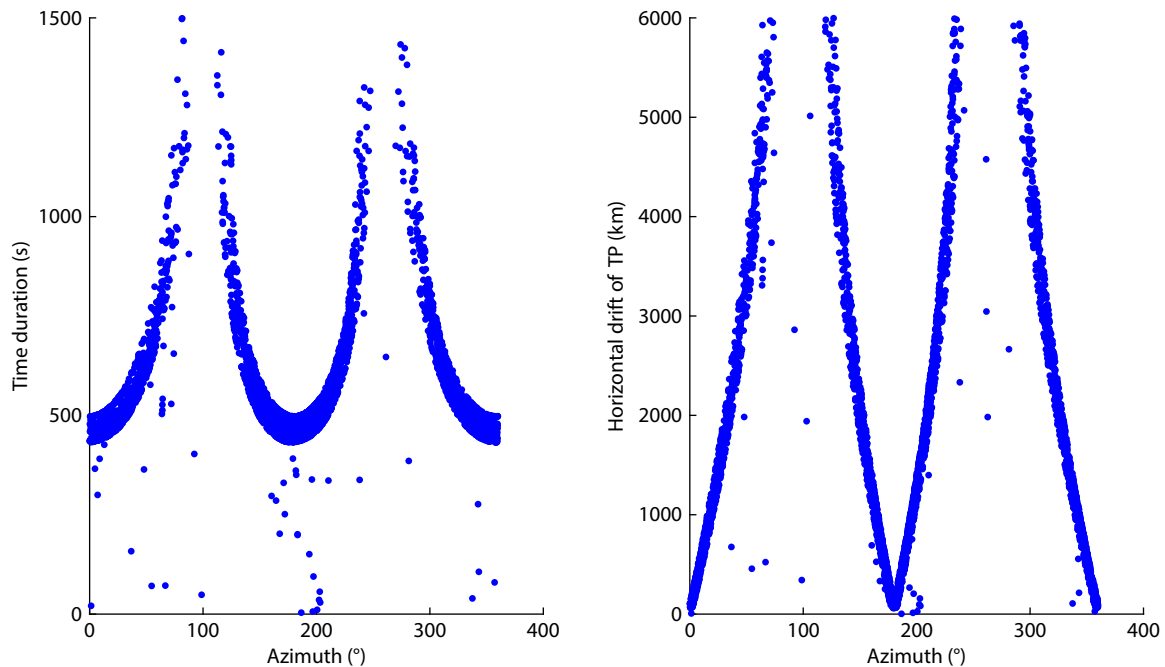
Figure 4. Distribution of latitude, longitude, stellar elevation angle, and azimuthal angle of the tangent point at the onset of the ionospheric occultation.

Table 2. Comparison of starlight normal and side occultation parameters.

	Normal		Side	
	Mean	Standard deviation	Mean	Standard deviation
Duration (s)	500.3898	58.6189	1283.47	936.9728
Horizontal drift of the occultation tangent point (km)	1245.83	856.51	7602.65	5335.27
Latitude span (°)	5.0201	5.5448	41.5471	36.1849
Longitude span (°)	17.6737	22.4078	77.3355	57.6836
Elevation span (°)	28.8094	2.3358	22.0675	11.6039
Azimuth span (°)	3.1114	2.6899	17.3263	14.4775

Table 3. Comparison of radio normal and side occultation parameters.

	Normal		Side	
	Mean	Standard deviation	Mean	Standard deviation
Duration (s)	612.15	99.87	1282.38	1022.03
Horizontal drift of the occultation tangent point (km)	899.33	520.55	3479.49	3165.27
Latitude span (°)	4.49	3.70	24.38	26.11
Longitude span (°)	15.81	27.60	35.31	44.31
Elevation span (°)	35.15	2.82	29.15	13.24
Azimuth span (°)	6.25	4.16	16.55	12.80

**Figure 5.** Variation in the ionospheric occultation duration and the occultation tangent point horizontal drift with the azimuth angle.

indicates the satellite's direction of motion). At 0°, 180°, and 360° azimuths, the star aligns with the LEO orbital plane, while increasing deviation reduces the star's projected velocity in the orbital plane, thereby decreasing vertical velocity at the occultation cutoff point. Consequently, normal occultation stars with minimal duration, reduced horizontal drift, and limited tangent point height variations are preferred for inversion, assuming negligible large-scale ionospheric perturbations.

Among these, elevation angle refers is defined as the elevation

angle E of the star in the local vertical-local horizontal (LVLH) coordinate system (also known as the local Cartesian coordinate system) of the LEO satellite. The LVLH coordinate system is defined as follows:

$$\mathbf{x} = \mathbf{v}, \mathbf{y} = \mathbf{r}_{\text{leo}} \times \mathbf{v}, \mathbf{z} = \mathbf{x} \times \mathbf{y}, \quad (12)$$

$$\sin E = \frac{\mathbf{z} \cdot \mathbf{r}_0}{\|\mathbf{z}\| \cdot \|\mathbf{r}_0\|}, \quad (13)$$

where $\mathbf{v}$ denotes the velocity of the LEO satellite, $\mathbf{r}_{\text{leo}}$ is the vector

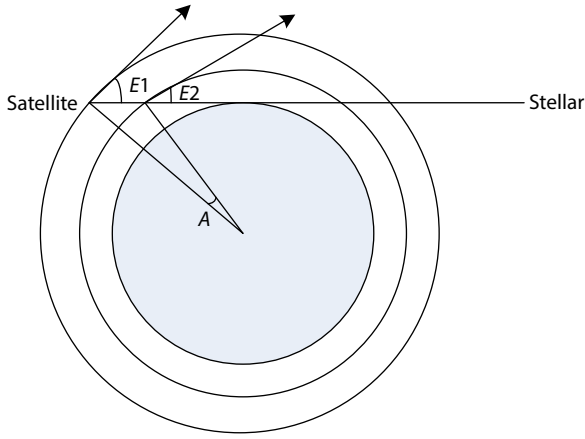


Figure 6. Satellite geometric composition (Wu XC, 2008).

from the Earth's center to the LEO satellite, and r_0 is the vector from the LEO satellite to the star. The elevation angle (denoted as E in Figure 6) and the azimuth angle (denoted as A) are primarily determined by the satellite's geometric configuration and vary with changes in the LEO orbit or the target altitude. This figure can be used to demonstrate how the elevation and azimuth angles change as the satellite orbital altitude varies. According to research, under the same orbital conditions, the elevation angles of GPS satellites relative to LEO satellites in ionospheric radio occultation are mainly concentrated around -17.5° and 17.5° . The primary reason for the inconsistency in elevation angle distributions between ionospheric stellar occultation and ionospheric radio occultation lies in the fact that the altitude distribution of GPS satellites is relatively fixed, and their positions can be fully determined by the orbital elements. In contrast, stars are randomly and irregularly distributed across all 88 constellations, with inconsistent distances from Earth. This results in differences in the geometric configurations of the satellites employed by the two technologies, thereby leading to discrepancies in the simulated elevation angles between the two measurement techniques.

Based on the selected band in this study, a star with UV apparent magnitude 0.1 (Sirius, with celestial coordinates RA 6h45m, Dec $-16^\circ 43'$, spectral type A1V) was selected as the signal source for occultation event simulation. The simulation yielded 31 daily occultation events, with their spatial distribution illustrated in Figure 7, where red markers denote individual occultation events.

The current simulation, as an idealized case, does not account for solar effects. This provides an upper bound on the number of potential occultation events. However, in practical applications, to mitigate solar background contamination, such constraints are necessary. Therefore, considering solar influence through zenith angle constraints will inevitably reduce the available target source count and daily observation frequency compared to this idealized upper bound. Future work will focus on incorporating these constraints into the operational simulation model.

3.3 Ionospheric Occultation Orthogonal Modeling

Based on observable spectral simulations, we determined the positional and kinematic parameters of both stars and satellites during stellar occultation events (Sun MC et al., 2020). The three-

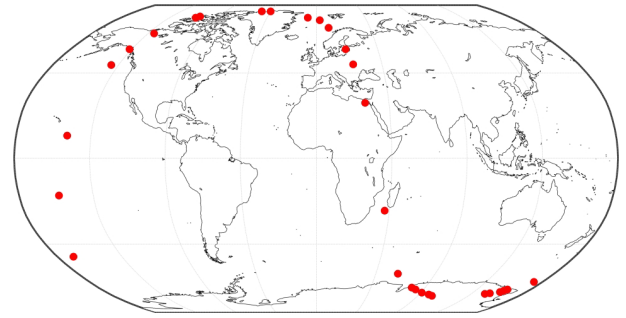


Figure 7. Single-day occultation events.

dimensional ray tracing method was employed to simulate the light path l through the ionosphere and calculate the transmittance rate T of the characteristic spectral lines, as expressed in Equation (14). These simulations elucidate the physical process of the occultation observation and systematically characterize the spectral signatures and their temporal evolution. Additionally, it offers a novel approach to develop inverse calculation algorithms.

$$T_{\text{abs}} = \exp\left(-\sum_i \sigma_i N_i(z)\right) = \exp\left(-\sum_i \int_i \sigma_i(\lambda, T(r(s))) \rho_i(r(s)) ds\right). \quad (14)$$

The parameters are defined as follows: σ represents the absorption cross-section; N_i denotes the column density of O^+ along the line of sight; λ corresponds the wavelength of the characteristic spectral lines; $T(r(s))$ indicates the temperature; and ρ signifies the number density of O^+ . The relevant spectral bands and corresponding absorption cross-section σ of O^+ are tabulated in Table 4 (Fennelly and Torr, 1992).

The simulation comprehensively incorporated ionospheric refraction effects. Using the model IRI2016 (Timoçin et al., 2018; Arkan et al., 2019) to obtain the required O^+ density for forward projection. This model provides global hourly values, electron density profiles, and monthly average characteristic parameter maps,

Table 4. Absorption cross-sections for different bands of O^+ .

Wavelength (Å)	$\sigma (\times 10^{-22} \text{ m}^2)$
50–100	0
100–150	1.460
150–200	3.368
200–250	4.281
256.30	4.910
284.15	5.900
250–300	5.332
303.31	5.940
320	5.51
350	4.91
400	4.79
500	5.51
600	2.93
650	1.08
684.8–1000	0

including proximity frequency variation maps, under specified solar activity conditions. Furthermore, the model was based on measured data, generating monthly averages of electron density, electron temperature, ion density, and ion composition across the 60–2000 km altitude range.

For simulation trajectories exceeding 2000 km altitude, the model's inability to provide electron density data necessitated setting these values to zero. The consequence was that if the sampling rate of the ray paths below 2000 km was low, it resulted in very small changes in the transmittance rate. The occultation paths calculations employed a three-dimensional ray-tracing approach, incorporating both ionospheric refraction effects and atmospheric background contributions.

Following light path determination, the transmittance was calculated using Equation (6), with refraction correction applied. The corresponding calculation results are presented in Figure 8.

The figure demonstrates minimal transmittance variation within this altitude range, primarily attributed to the limited number of sampling points below 2000 km traversed by the optical band during simulation, consequently reducing available integration path data points.

3.4 Inversion of Ionospheric Stellar occultation Simulation Data

Given the finite number of simulations, continuous equation reconstruction would inherently exhibit pathological characteristics due to insufficient data volume. To ensure system self-consistency, this study employs the peeling onion method, which operates under the following fundamental assumptions: the atmosphere is symmetrically layered, stratifies the atmosphere, and assumes that the concentration of trace gases is kept constant at each layer, while the variation of the observed radiation at each

layer is only related to the tangent heights at the current and neighboring upper layers of the observations are correlated. The schematic diagram is illustrated in Figure 9.

The inversion principle is shown in Equation (15):

$$\begin{aligned} \frac{1}{2} T_i - \sigma_1 \rho_1 (S_i - \sqrt{R_1^2 - R_i^2}) - \sum_{j=2}^i \sigma_j \rho_j (\sqrt{R_{j-1}^2 - R_i^2} - \sqrt{R_j^2 - R_i^2}) \\ = \sigma_i \rho_i \sqrt{R_{i-1}^2 - R_i^2}, \end{aligned} \quad (15)$$

where T_i denotes the transmittance, σ represents absorption cross-sectional area, ρ indicates ion density, and S corresponds to the light integration path. The simulated transmittance data were employed for inversion, with the inversion results compared against model results, as presented in Figure 10. The figure provides a comparative visualization of inversion results across different paths relative to the reference model.

The inversion results demonstrate strong agreement with IRI

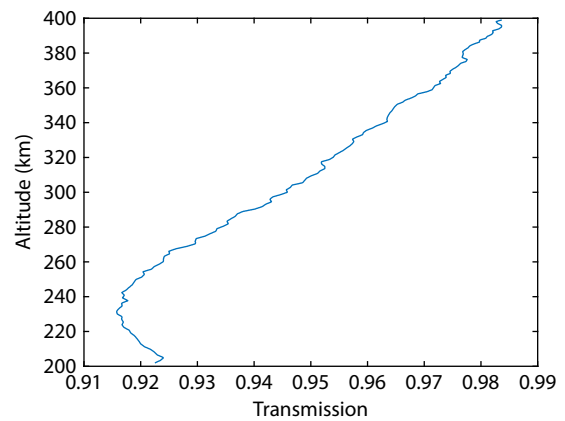


Figure 8. Variation in the atmospheric radiation transmittance with height.

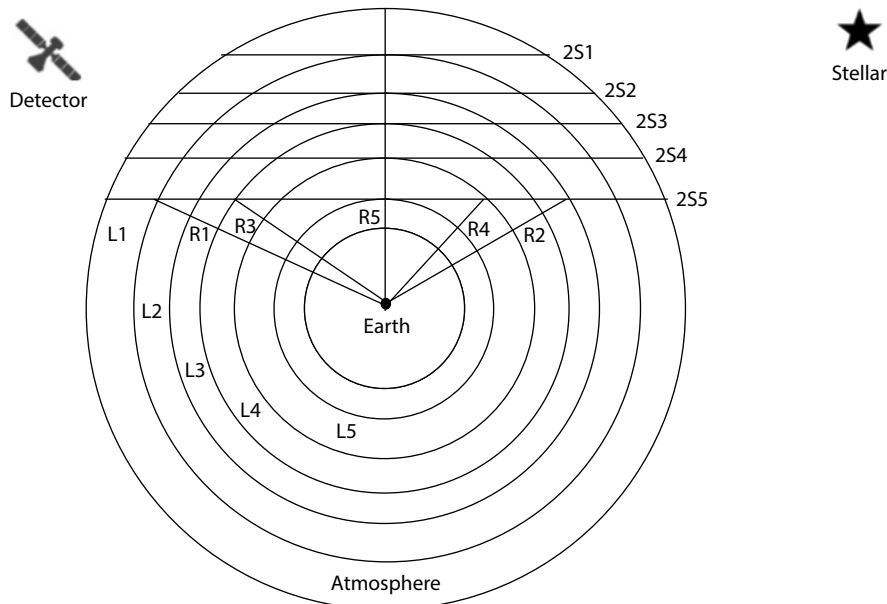


Figure 9. Inversion schematic of onion-peeling. The R represents the distance between the occultation tangent and the center of the Earth, L denotes the stratification of the Earth's atmosphere, and S indicates the straight-line distance of the occultation event through the Earth's atmosphere (Sun MC, et al., 2022).

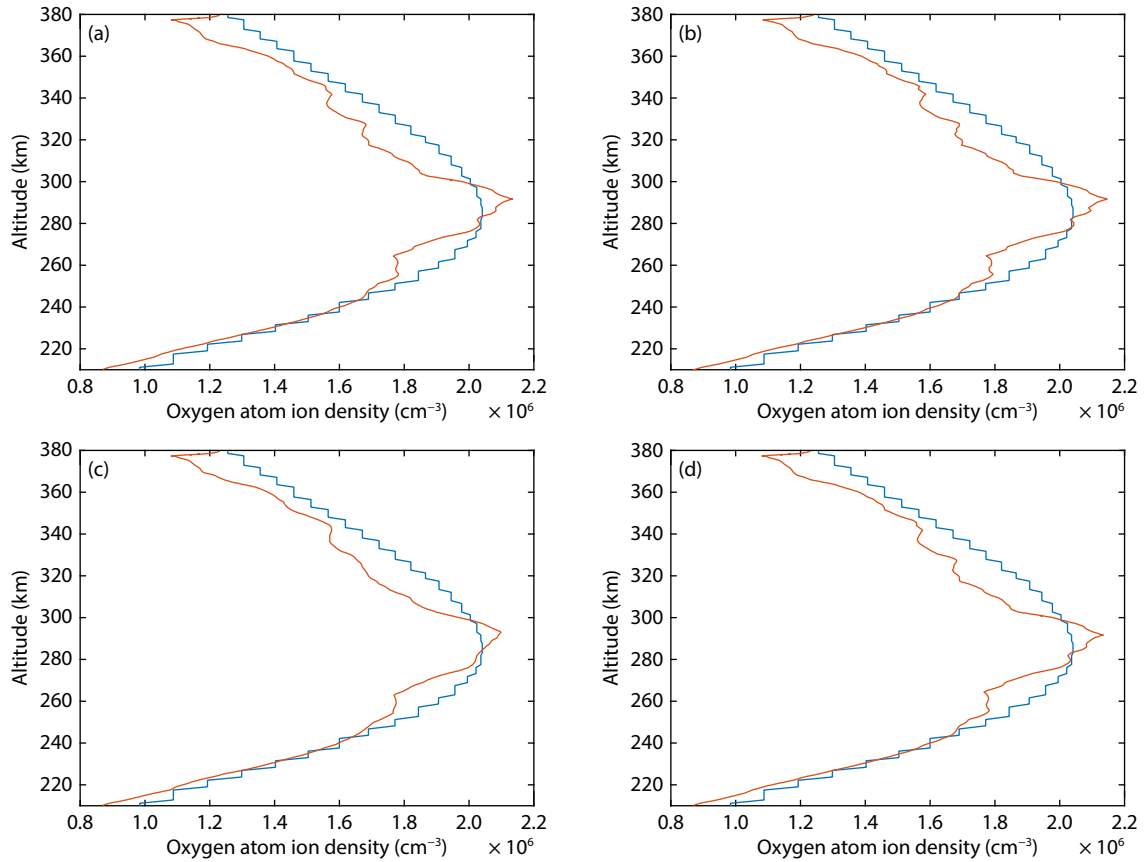


Figure 10. Retrieved vertical profiles of O^+ density compared with the IRI model for four cases. (a) Case1; (b) Case 2; (c) Case 3; and (d) Case 4. The red line is the simulation inversion result, and the blue line is the IRI model result.

model results, particularly in regions of high parameter values, confirming the self-consistent property of the forward and inversion models in this study. Furthermore, the inversion results maintain satisfactory consistency with established reference data, thereby validating the feasibility of stellar occultation ionospheric observation techniques.

The inversion method's reliability was assessed through relative error calculation, comparing results with model outputs using Equation (16), and the corresponding variations in the relative error are presented in Figure 11, where N_e denotes the electron density.

$$r = \frac{N_e(\text{inversion}) - N_e(\text{model})}{N_e(\text{model})}. \quad (16)$$

Comparative analysis between the inversion results and the IRI model outputs reveals the inversion error peak below 2%, attributable to three primary factors: (1) substantial height intervals in input data causing significant fitting errors; (2) inherent uncertainties in the IRI model itself; and (3) unaccounted variations in single-wavelength absorption cross-sections with altitude. It is crucial that this study exclusively addresses simulation-induced errors, while potential uncertainties from orbital and positioning inaccuracies remain subjects of ongoing investigation. Based on the above results, we compare the key indicators of the two occultation techniques. As shown in Table 5, the research results indicate that radio occultation has the advantages of long-term stability, high accuracy, and high vertical resolution, but it does not have

the advantage of high temporal resolution.

4. Conclusions

Through comprehensive quantitative analysis, this study establishes ionospheric stellar occultation as a promising technique for global ionospheric electron density monitoring, offering significant advantages, including abundant target sources, high event frequency, global ionospheric monitoring capability, enhanced vertical resolution, and elimination of absolute calibration requirements. The main conclusions are as follows:

- (1) A total of 141 ultraviolet stellar sources with apparent magnitudes between -1.46 and 4 were identified as suitable occultation sources based on SNR criteria.
- (2) Under identical orbital conditions (CHAMP), stellar occultation yields 4414 daily events, approximately five times more than GPS radio occultation (862 events), demonstrating significantly higher temporal resolution.
- (3) The inversion error at the electron density peak (NmF2) remains below 2%, with even smaller errors at lower altitudes, confirming the feasibility and practicability of the proposed technique.
- (4) Stellar occultation offers advantages including global coverage capability, high vertical resolution (~ 1 km), and elimination of absolute calibration requirements.

This technique holds the potential to advance fundamental understanding of ionospheric dynamics, facilitate precision space

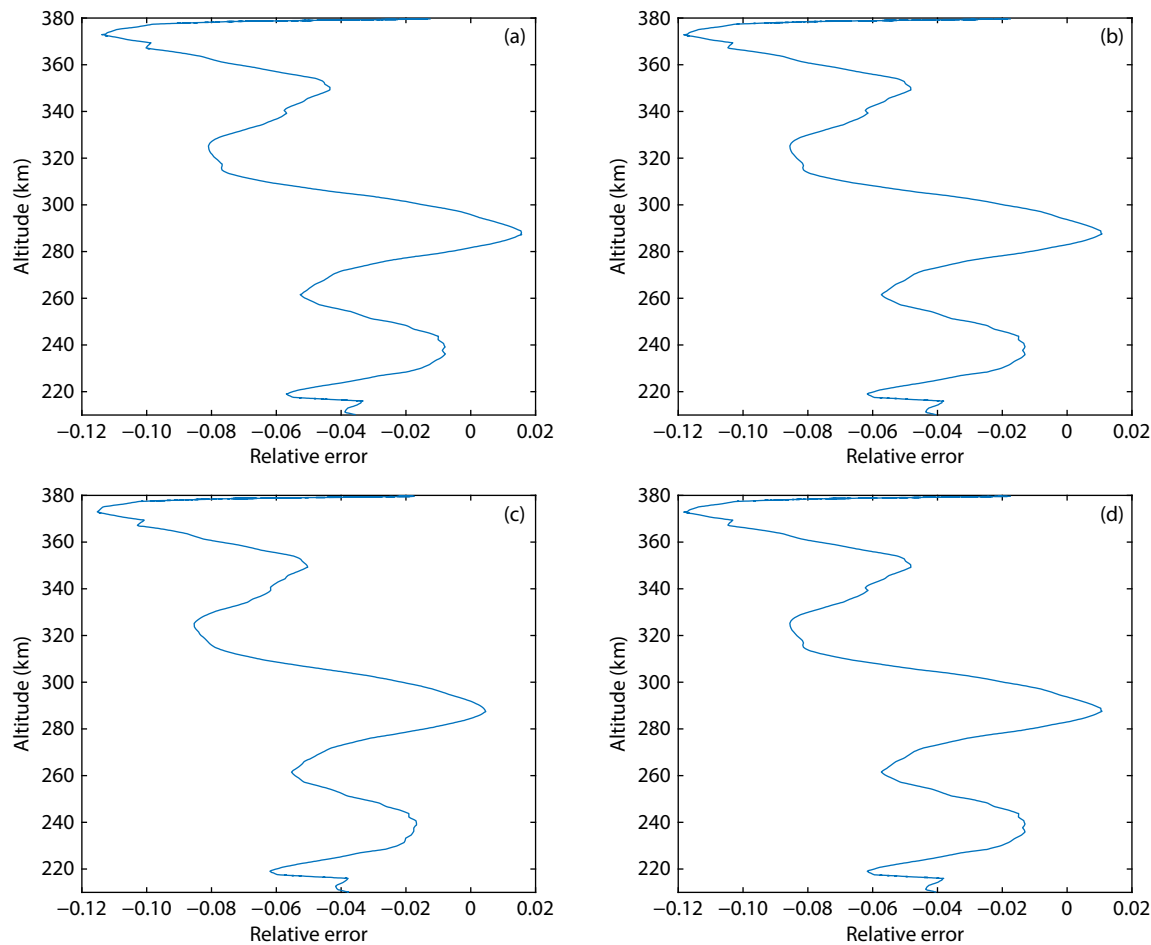


Figure 11. The corresponding variations in the relative error for the four cases. (a) Case1; (b) Case 2; (c) Case 3; and (d) Case 4.

Table 5. Comparison of key indicators for stellar occultation and GPS occultation.

Key indicators	Stellar occultation	Radio occultation
Vertical resolution	Around 1 km	Around 1 km
Temporal resolution	0.5 s	—
Coverage	Global coverage	Global coverage
Accuracy (normal weather conditions)	2%	3%
Data volume	4414	862

weather forecasting, and enable sustained global ionospheric monitoring with high temporal stability. While providing preliminary technological validation, the present study identifies several limitations that warrant further investigation. It should be noted that the assumption of O^+ being the dominant ion ($\approx 95\%$ of the electron density) is a commonly adopted approximation in ionospheric studies, particularly in the F-region where O^+ is the major constituent. However, this approximation is not universally valid. The O^+ fraction varies with altitude (peaking around 250–400 km), local time (higher during daytime due to photoionization), latitude (equatorial anomalies and auroral effects), and solar activity (enhanced ionization under high solar flux). Additionally, during geomagnetic storms or at high latitudes, the relative abundance

of O^+ can decrease due to ion composition changes, and contributions from other ions such as O_2^+ , NO^+ , and N_2^+ may become non-negligible. In this study, we limit our analysis to quiet mid-latitude daytime conditions, where the 95% O^+ assumption is justified by empirical data (e.g., from the IRI model and previous rocket/incoherent scatter measurements). For more disturbed or extreme conditions, the retrieval algorithm would need to incorporate a more realistic ion composition model, which we plan to explore in future work. To advance autonomous development of ionospheric stellar occultation technology, future research will prioritize:

- (1) Systematic analysis of inversion errors across multiple spectral bands, with emphasis on identifying optimal UV bands for monitoring application based on signal-to-noise ratio criteria.
- (2) Systematic analysis of the impact of orbital and positioning errors on inversion models in practical applications.
- (3) Development of dedicated occultation monitoring constellations and real-time event prediction models, incorporating solar influence through zenith angle parameterization during occultation simulations.
- (4) Enhancement of IRI model input data accuracy through correction algorithms or high-precision electron density measurements, complemented by integration of diverse inversion methodologies to improve detection precision.
- (5) Development of an effective cross-sectional method for data inversion, coupling spectral inversion and vertical inversion

through effective cross-sections, which can more straightforwardly solve the non-physical oscillation problems that arise during the inversion process.

(6) Implementation of line-by-line integration techniques for precise absorption cross-section calculations along actual occultation paths, thereby reducing systematic errors.

(7) Design and validation of satellite payload systems specifically optimized for ionospheric stellar occultation, with concurrent verification of algorithm applicability in operational scenarios.

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