

Postprint: Propagation Medium Error Correction Method for Ground-Based Measurement Data in Deep Space Exploration

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Abstract

In deep space exploration, probe orbits are primarily measured using ground tracking stations. Radio signals transmitted between the probe and ground tracking stations are affected by Earth propagation medium errors. These errors mainly include neutral atmospheric delay errors and ionospheric delay errors. To address the application requirements of propagation medium error correction in deep space exploration, research progress on propagation medium errors in ground-based measurement data both domestically and internationally has been investigated, with emphasis on elaborating the mechanisms and correction methods for neutral atmospheric and ionospheric delays in VLBI ground-based measurement data. Key technologies and future development trends are analyzed to improve the accuracy and timeliness of propagation medium error correction.

Full Text

Preamble

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Methods for Propagation Medium Error Correction in Ground-Based Measurement Data for Deep Space Exploration

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Abstract

In deep space exploration, spacecraft trajectories are primarily measured using ground tracking stations. Radio signal transmission between the spacecraft and ground stations is affected by Earth's propagation medium errors, which mainly include neutral atmospheric delay errors and ionospheric delay errors. In response to the application requirements for propagation medium error correction in deep space exploration, this paper investigates research progress on propagation medium errors in ground-based measurement data both domestically and internationally, with emphasis on the mechanisms and correction methods for neutral atmospheric and ionospheric delays in VLBI ground-based measurement data for deep space exploration. Key technologies and future development trends are analyzed to improve the accuracy and timeliness of propagation medium error correction.

Keywords: deep space exploration; neutral atmospheric delay; ionospheric delay

1 Introduction

Since the late 1950s, countries and organizations including the United States, Russia (former Soviet Union), European Union, China, and Japan have conducted over 250 deep space exploration missions. Exploration targets have essentially covered all types of celestial bodies within the solar system, with some spacecraft successfully landing on or returning from the Moon, Mars, and asteroids. Deep space exploration projects have yielded numerous scientific discoveries, providing an important foundation for human understanding of the universe [?].

After spacecraft launch, tracking and observation are required. The United States employs the NASA Deep Space Network (DSN) to track spacecraft, which consists of three tracking stations spaced 120° in longitude and a mission operations control center in California. The three stations are the Goldstone station in California, the Madrid station in Spain, and the Canberra station in Australia. This globally distributed deep space network enables continuous tracking of targets as the Earth rotates [?]. Due to its high angular measurement precision, the U.S. Very Long Baseline Array (VLBA) is also used for spacecraft tracking; for example, the Cassini mission to Saturn utilized the 10-station VLBA array for tracking [?]. The Russian (former Soviet Union) deep space network comprises three tracking stations, two command centers, and two ballistic centers. The three ground stations are Ussuriysk, Yevpatoriya, and Bear Lake, with approximately 100° longitude separation between the eastern and western stations

[?]. The European deep space network consists of three tracking stations and the European Space Operations Centre. The three stations include New Norcia in Australia, Cebreros in Spain, and Malargüe in Argentina [?]. Additionally, the European VLBI Network (EVN) participates in deep space exploration missions [?]. The deep space network managed by the Japan Aerospace Exploration Agency 主要包括臼田、鹿儿岛等深空站和相模原控制中心。另外，日本国立天文台的 4 个 VLBI 测站也参与了深空探测，包括水泽、入来、小笠原和石垣岛 VLBI 站 [?]. China's deep space tracking system mainly includes three tracking stations and a control center in Beijing. The three stations are located in Kashgar, Jiamusi, and Zapala, Argentina [?]. Additionally, the Chinese VLBI Network (CVN) also undertakes China's deep space exploration tasks, with four radio telescope tracking stations in Beijing, Shanghai, Kunming, and Urumqi, and a VLBI data processing center in Shanghai [?].

During spacecraft flight, high-precision tracking measurements using ground stations are required to accurately determine the flight trajectory, particularly during critical arcs such as mid-course orbital maneuvers and braking upon arrival at the target. Whether the spacecraft can successfully reach its designated position is crucial to mission success. Early deep space spacecraft orbit determination employed ranging and Doppler velocity measurements to determine the spacecraft's distance and velocity along the line of sight, with long-arc Doppler velocity measurements indirectly providing angular information in the plane to complete orbit determination. Spacecraft orbits depend on the dynamic model of observations and station coordinates. Errors affecting ranging and velocity measurements include station clock instability, propagation medium errors, instrument errors, station coordinate errors, and errors caused by Earth rotation parameters. Long-arc observations accumulate measurement errors, affecting accuracy. As deep space exploration missions progress, especially during critical mission phases such as landing and return, more precise spacecraft position determination is required.

In the 1980s, VLBI technology from radio astronomical observations began to be applied in deep space exploration. This technique involves two or more antennas receiving signals from the same spacecraft or extragalactic radio source simultaneously, followed by correlation processing to obtain observables. The advantage of this interferometric measurement is that baseline lengths can reach thousands of kilometers, greatly improving spatial angular resolution and enabling more precise determination of spacecraft angular information. VLBI measurement errors are divided into two categories: model and parameter errors caused by inaccurate astrometric, geophysical parameters, or models; and errors caused by station time-frequency system instability, station signal reception system-induced phase jitter, and propagation medium delay effects. By alternately observing extragalactic radio sources near the spacecraft, common instrument and station errors can be eliminated. However, propagation medium-induced delay errors vary with time, and the angular separation between spacecraft and radio sources ranges from several to more than ten degrees, resulting in different medium delays along different paths (see Figure 1 [Figure 1: see

original paper]).

Propagation media affecting deep space exploration signals include Earth's space environment and interplanetary space environment. This paper focuses on the mechanisms, correction methods, and research status of neutral atmospheric and ionospheric delays in Earth's space environment in deep space exploration ground-based measurement data, while briefly introducing solar plasma-induced delay correction methods.

2 Neutral Atmosphere

The neutral atmosphere discussed in this paper primarily refers to the atmosphere from Earth's surface to about 50 km altitude, including the troposphere and stratosphere. The height of the troposphere varies with latitude: 17–18 km in low-latitude regions, 10–12 km in mid-latitude regions, and 8–9 km in polar regions.

2.1 Mechanism of Neutral Atmospheric Delay Error

The atmosphere affects electromagnetic wave propagation in two ways: (1) the propagation speed slows compared to vacuum, and (2) the propagation path bends from a straight line. Both effects are caused by changes in atmospheric refractive index along the propagation path. The signal propagation time delay is equivalent to an increase in propagation path length, expressed as:

$$\Delta L = c_0 \Delta t \langle MATH_0 \rangle G = c_0 \langle MATH_1 \rangle G = \int_L n(s) ds \langle MATH_2 \rangle G$$

where ΔL is the path increase due to neutral atmospheric delay, c_0 is the speed of light in vacuum, Δt is the actual signal propagation time, G is the geometric path length between spacecraft and receiver, L is the bent path, c is the signal propagation speed in the atmosphere, and $n(s)$ is the atmospheric refractive index.

$$[n(s) \langle MATH_3 \rangle 1 + 1] ds \langle MATH_4 \rangle G = [n(s) \langle MATH_5 \rangle 1] ds + S \langle MATH_6 \rangle G$$

where S is the path length along L . The first integral term on the right is the slowing term; the second term is the bending term, representing the difference between the bent path and the straight path. Bending delay shows significant differences at low spacecraft elevation angles ($< 5^\circ$) (approximately 2 m), but is much smaller than propagation speed delay. At 15° elevation, bending delay is on the order of ten centimeters and approaches zero as elevation increases, becoming negligible [?].

Neutral atmospheric delay magnitude primarily depends on atmospheric thickness along the electromagnetic wave propagation path and meteorological parameters (including temperature, humidity, and pressure) at each point. Characteristics include: (1) large variation amplitude, approximately 2.3 m in the zenith direction and up to 30 m at low elevation angles; (2) non-dispersive below 30 GHz [?], making it impossible to eliminate using frequency combination methods; (3) strong randomness in atmospheric water vapor distribution, making modeling difficult; (4) significant differences across regions and seasons, making global modeling challenging.

Neutral atmospheric delay varies with elevation angle and can be approximated as the product of zenith delay and the reciprocal of the sine of the observation elevation angle. VLBI technology for spacecraft tracking employs differential observations, with a certain angular separation between spacecraft and extragalactic radio sources. Therefore, neutral atmospheric delay is highly correlated with elevation angle and spacecraft-radio source angular separation [?], as shown in:

$$\langle MATH_7 \rangle \Delta\tau_{tro} \langle MATH_8 \rangle \varepsilon \sin el_T \sin el_C$$

where $\Delta\tau_{tro}$ is the differential delay caused by different observation elevations, ε is the precision of atmospheric zenith delay, and el_T and el_C are the observation elevation angles of the spacecraft and extragalactic radio source, respectively.

Figure 2 [Figure 2: see original paper] shows the relationship between neutral atmospheric delay error effects on orbit determination delay and elevation angle and spacecraft-radio source angular separation. The zenith neutral atmospheric delay error is set to 2 cm in the figure, with angular separations of 2°, 5°, and 8°. When the elevation angle is 10° and angular separation is 8°, a 2 cm zenith neutral atmospheric delay error can affect orbit determination delay by up to 170 ps. Note: red represents 8° separation; black represents 5° separation; blue represents 2° separation.

Therefore, selecting reference sources with small angular separation and avoiding low-elevation observations can reduce neutral atmospheric delay effects. However, sufficiently bright radio sources are often unavailable under small angular separation conditions. To increase baseline length, stations are often separated by thousands of kilometers, making it impossible for all stations to meet elevation angle requirements during simultaneous observations. Additionally, neutral atmospheric delay errors are highly correlated with station coordinates and receiver clock errors, making it impossible to eliminate their effects through parameter estimation methods [?]. Using external data for neutral atmospheric delay correction is therefore an essential calibration process.

2.2 Neutral Atmospheric Delay Correction Methods

This paper investigates and analyzes neutral atmospheric delay correction methods for tracking stations domestically and internationally. Currently commonly used methods include the zenith delay + mapping function method and the Water Vapor Radiometer (WVR) based correction method.

2.2.1 Zenith Delay + Mapping Function Method Expressing signal delay in the spacecraft direction as a combination of zenith delay and an elevation-dependent mapping function is currently an effective correction method for neutral atmospheric delay in ground-based measurement data for deep space exploration.

2.2.1.1 Neutral Atmospheric Zenith Delay (1) U.S. Spacecraft Neutral Atmospheric Zenith Delay Correction Method

Beginning in the 1970s, the U.S. Deep Space Network primarily adopted the seasonal model proposed by Chao for neutral atmospheric zenith delay correction [?]. Compared with radiosonde results, this model's zenith wet delay 1σ precision is about 2 cm. As it does not require measured data, this model can be used as a prediction model for real-time neutral atmospheric delay correction.

With increasing requirements for spacecraft orbit determination accuracy, the original seasonal model can no longer meet neutral atmospheric delay correction needs. The Jet Propulsion Laboratory (JPL) proposed a polynomial model for neutral atmospheric delay correction [?], using time-normalized Fourier series to represent zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD), as shown in Equation (4):

$$F_s(X) = A_0 + A_1 \langle MATH_9 \rangle \cos(X) + B_1 \langle MATH_{10} \rangle \sin(X) + A_2 \langle MATH_{11} \rangle \cos(2X) + B_2 \langle MATH_{12} \rangle \sin(2X) + \dots$$

$$X = 2\pi \langle MATH_{18} \rangle T \langle MATH_{19} \rangle S$$

where A_i, B_i are fitted Fourier coefficients, N is the order of the Fourier series expansion, T is the calibration time, S is the start time, P is the fundamental mode period, all in seconds.

The first-order term of the polynomial model is the seasonal model proposed by Chao [?], with parameters expressed as time-normalized Fourier series. To avoid double calibration, based on seasonal model calibration, near-real-time meteorological data and Global Positioning System (GPS) observation data are used to calculate incremental correction time series for neutral atmospheric zenith delay, hydrostatic delay, and wet delay, expressed using time-normalized polynomials as shown in Equation (5):

$$P_y(X) = C_0 + C_1 \langle MATH_{20} \rangle X + C_2 \langle MATH_{21} \rangle X^2 + \langle MATH_{22} \rangle \langle MATH_{23} \rangle \langle MATH_{24} \rangle + C_N \langle MATH_{25} \rangle X^N$$

$$X = 2 \langle MATH_{26} \rangle \langle MATH_{27} \rangle 1, T \langle MATH_{28} \rangle SE \langle MATH_{29} \rangle S$$

where C_i are fitted polynomial coefficients, N is the order of the polynomial expansion, T is the calibration time, S is the start time, and E is the end time.

Global Navigation Satellite System (GNSS) is closely related to neutral atmospheric refraction delay. On one hand, satellite signals experience delay errors when passing through the neutral atmosphere due to refraction; on the other hand, this effect can be used to retrieve neutral atmospheric delay quantities through GNSS technology. Due to its all-weather, high-sampling, high-precision, and weather-independent advantages, GNSS technology is an important means for neutral atmospheric delay correction. This technology has been successfully applied to neutral atmospheric delay correction in deep space exploration ground-based measurement data. The slant path delay (SPD) along the propagation path can be expressed through zenith delay, mapping function, and gradients as follows:

$$SPD = m_{fh} \langle MATH_{30} \rangle ZHD + m_{fw} \langle MATH_{31} \rangle ZWD + m_{fg} \langle MATH_{32} \rangle (G_N \cos \alpha + G_E \sin \alpha)$$

where m_{fh} and m_{fw} are hydrostatic and wet delay mapping functions, ZHD and ZWD are zenith hydrostatic and wet delays, m_{fg} is the gradient mapping function, G_N and G_E are north-south and east-west horizontal gradients, and α is the azimuth.

The U.S. Deep Space Network's method for retrieving neutral atmospheric delay based on GPS technology treats neutral atmospheric zenith total delay as an estimable parameter, using least squares or Kalman filtering for post-processing or real-time processing. The data processing software uses GIPSY-OASIS developed by JPL. The average difference in zenith wet delay estimated by this software and Bernese software developed by the University of Bern is 6 mm, with a standard deviation of 3.2 mm. Since GNSS technology can only obtain neutral atmospheric zenith total delay, to obtain wet delay, the Saastamoinen model is used to calculate hydrostatic delay based on collocated meteorological data, and wet delay information for deep space stations is obtained by subtracting hydrostatic delay from the total neutral atmospheric delay retrieved from GNSS observations.

During orbit determination for the 2001 U.S. Mars Odyssey spacecraft, neutral atmospheric delay in ground-based measurement data was provided by JPL [?], using the GPS technology processing method described above. In 2007, JPL used this GPS technology to obtain neutral atmospheric delay for calibrating

Deep Space Station Δ DOR, VLBI, and VLBA observations [?]. In the same year, JPL proposed ZTD methods with 1-hour and 12-hour delays applicable to various bands of deep space antennas. The 1-hour delayed ZTD product provides correction precision at the centimeter level, while the 12-hour delayed ZTD product provides precision better than 1 cm. This method was applied to Cassini spacecraft orbit determination [?].

Additionally, the U.S. VLBA is also used for spacecraft orbit determination. When the U.S. VLBA determined the Cassini spacecraft orbit, approximately 15 strong radio sources were used to calibrate neutral atmospheric zenith delay. This method obtains multi-band delays by rapidly observing strong radio sources across a wide elevation angle range, then projects them to the spacecraft observation direction using the Chao mapping function [?].

(2) European Spacecraft Neutral Atmospheric Zenith Delay Correction Method

The commonly used neutral atmospheric delay correction method for the European Deep Space Network is the Saastamoinen model [?]. This method calculates neutral atmospheric delay based on measured meteorological data and can be used for post-processing correction. Due to the non-uniform distribution of water vapor in the atmosphere, this method achieves high precision for ZHD but poor precision for ZWD, at the centimeter level. Based on cooperation agreements, neutral atmospheric delay correction for the European Deep Space Network is also supported by JPL.

In recent years, to be independent of external data, the European Deep Space Network has developed an independent neutral atmospheric delay correction platform based on the polynomial correction algorithm proposed by JPL. Main components include: (1) The navigation office provides ZTD and ZWD for deep space stations over 48-hour periods retrieved using GNSS technology. (2) Each European deep space station is equipped with a meteorological instrument providing 1-minute sampled temperature, humidity, and pressure information. ZHD is calculated based on the Saastamoinen model. When pressure data is unavailable, the Global Pressure and Temperature (GPT) model is used [?]. (3) Corrections are made for ZHD differences caused by height differences between deep space station antennas and International GNSS Service (IGS) tracking stations. The deep space station reference point is the intersection of the antenna azimuth and elevation axes. Specific methods are referenced in [?]. (4) Fast and final modes are distinguished based on the number of GNSS stations participating in the solution. The final mode has a 4-day delay. (5) The neutral atmospheric delay polynomial is of 4th order, with polynomial coefficients estimated using least squares. Figure 3 [Figure 3: see original paper] shows the timing scheme for the European navigation office's development of ZWD, ZHD, and calibrated neutral atmospheric delay correction platform, with calculations starting daily at 14:30 UT for 48 hours of observation data from 12:00 UT of the current day.

The European VLBI Network (EVN) is also used for spacecraft orbit tracking, such as during the Vega Halley comet probe's Venus atmospheric detection, the Huygens probe's landing on Titan's surface [?], ESA's Smart-1 probe's lunar surface control phase, the final cruise phase of U.S. Mars Rover B [?], the Cassini Saturn probe [?], and more recently the Venus Express probe [?]. When using EVN for orbit determination, neutral atmospheric delay errors are corrected using two methods: (1) empirical models and Vienna Mapping Functions 1 (VMF1); (2) ray tracing technology [?], which is specifically introduced later. The second method is used at low elevation angles or when the spacecraft-radio source angular separation is large, such as in Venus Express tracking mission EM081c [?].

(3) Japanese Spacecraft Neutral Atmospheric Zenith Delay Correction Method

In 2007, Japan's SELENE spacecraft was launched. The Japanese radio astronomy VLBI network and international VLBI network (including Shanghai and Urumqi in China, Hobart in Australia, and Wettzell in Germany) used multi-frequency VLBI technology for SELENE orbit determination. When Liu et al. determined SELENE's orbit based on VLBI same-beam technology, neutral atmospheric delay was corrected using GPS technology. ZHD was calculated using station pressure values with 1 mm precision; ZTD was processed using GpsTools software, with orbit and clock files from final products on the IGS website, achieving 10 mm ZTD precision [?]. Additionally, based on cooperation agreements, Japanese spacecraft are also tracked by U.S. deep space stations.

(4) Chinese Spacecraft Neutral Atmospheric Zenith Delay Correction Method

China's deep space exploration started later than the U.S. and Europe but has developed rapidly. For neutral atmospheric delay correction, in 2014, Zhao et al. fitted refraction attenuation coefficients based on historical meteorological data at stations, established a neutral atmospheric refractivity model for Chinese tracking stations, and optimized the statistical model using measured ground refractivity. This model was successfully applied to real-time correction of long-arc external measurement data for spacecraft [?]. In 2019, the Beijing Aerospace Flight Control Center constructed a regional high-precision neutral atmospheric delay model suitable for real-time deep space exploration missions. First, by comparing measured neutral atmospheric delay values with model values, correction coefficients for Saastamoinen model zenith delay estimation were determined, reducing neutral atmospheric zenith delay bias from 1.24 ns to about 0.9 ps. Second, to overcome meteorological data constraints of the Saastamoinen model, a regional atmospheric parameter estimation model was established based on the elevation-corrected UNB3m model. Estimation biases for atmospheric pressure, temperature, and water vapor pressure were approximately 390 Pa, 6.7 K, and 63 Pa, respectively, with neutral atmospheric zenith delay bias from atmospheric parameter model and measured values being about 14 ps. Using this method, real-time orbit determination residuals for the

Chang'e-4 spacecraft were basically consistent with results under post-processed neutral atmospheric delay measured values [?].

China's CVN also tracks deep space spacecraft, such as the Chang'e series and Tianwen-1 Mars probe. In recent years, based on three years of ZTD sequences from Beijing, Shanghai, Kunming, and Urumqi stations, the Shanghai Astronomical Observatory of the Chinese Academy of Sciences developed a localized zenith delay model for CVN stations [?]. This model does not require measured data and can be applied to real-time correction of propagation medium errors in VLBI observations. Based on analysis of Chang'e-5 measured data, the neutral atmospheric zenith total delay calculated by this model has RMS values of 0.11, 0.14, 0.03, and 0.08 ns at the four stations. After applying this model, VLBI delay residuals at low elevation angles (10° – 28°) are about 0.62 ns. The model expression is:

$$ZTD = ZTD_0 + A_1 \cos \frac{365.25 \langle MATH_{33} \rangle}{24} + B_1 \sin \frac{365.25 \langle MATH_{34} \rangle}{24} + A_2 \cos \frac{A_3 \cos 365.25 \langle MATH_{35} \rangle}{24} + B_2 \sin \frac{A_3 \cos 365.25 \langle MATH_{35} \rangle}{24}$$

where ZTD is the neutral atmospheric zenith delay at the station, ZTD_0 , A_i , B_i are fitting coefficients for individual stations, and $thoy$ is the hour of year, requiring determination of corresponding parameters and time points based on the station.

To further improve neutral atmospheric delay correction precision, the Shanghai Astronomical Observatory of the Chinese Academy of Sciences has implemented GNSS-derived neutral atmospheric delay correction technology with 1-hour updates based on GNSS measured data, applied to post-processing 3-hour mode of VLBI orbit determination. Through analysis of Chang'e-5 measured data, VLBI delay residuals at low elevation angles (10° – 28°) can reach 0.26 ns RMS [?].

2.2.1.2 Mapping Functions In the 1970s, the U.S. Deep Space Network adopted the mapping function model proposed by Chao et al. to project neutral atmospheric zenith delay to spacecraft observation direction [?]. In the 1980s, Lanyi, Davis, and Herring proposed the semi-analytical mapping function, CFA2.2 [?], and MTT [?] mapping functions. In the 1990s, Niell proposed NMF [?], and Yan Haojian et al. [?] established the UNSW model. For CFA2.2 and UNSW models, mapping function precision degrades quickly when surface meteorological records deviate significantly from model specifications. MTT and NMF models can better describe mapping functions for atmospheric profiles across the atmospheric variation range. However, due to limitations of radiosondes, correction precision varies globally.

The U.S. Deep Space Network, European Deep Space Network, Japanese VLBI network, and China's CVN primarily use the NMF model to project ZTD to spacecraft observation direction [?]. The European EVN uses the VMF1 model

to obtain neutral atmospheric delay correction in the spacecraft observation direction [?]. The Beijing Aerospace Flight Control Center analyzed NMF mapping function patterns, identified the dry mapping parameter a as the main influencing parameter, and further calculated the optimal value of parameter a using least squares. Results show that at 10° elevation angle, neutral atmospheric delay bias is about 0.3 ns, reduced by nearly an order of magnitude. This method was applied to Chang'e-4 real-time missions [?]. In recent years, China's CVN has adopted the GMF model for projection [?].

Since the 21st century, with the establishment of numerical weather models, the Vienna University of Technology has developed the VMF series models [?]. This series includes the first generation (GMF/VMF1/VMF1-FC), second generation (GPT2/GPT2w/VMF2), and third generation (GPT3/VMF3/VMF3-FC), with the third generation having the best precision. VMF1, VMF2, and VMF3 require measured grid data and can be used post-processing; GMF, GPT2, GPT2w, and GPT3 are empirical models applicable to real-time correction; VMF1-FC and VMF3-FC are models constructed using grid forecast products and can also be applied to real-time correction, though such grid forecast products require permissions to access. Wuhan University evaluated the modeling precision of the latest generation models for real-time neutral atmospheric mapping functions GPT3, VMF3-FC, and station-specific VMF3-FC using ray tracing. Station-specific VMF3-FC has the best precision; VMF3-FC is second best and recommended when station-specific products are unavailable; GPT3 performs worst overall but can be embedded in software and is recommended when grid forecast products cannot be downloaded [?]. Based on this, deep space stations can consider using such models to improve neutral atmospheric delay correction precision in spacecraft observation directions.

2.2.2 WVR-Based Neutral Atmospheric Delay Correction Method

Currently, the most precise neutral atmospheric delay correction method is based on WVR measurements, which can directly measure brightness temperature in the spacecraft observation direction and then estimate neutral atmospheric wet delay through specialized retrieval algorithms. Dry delay is obtained through retrieval algorithms based on pressure observed by WVR. This technology is affected by liquid water and may fail in heavy rain or cloudy weather, representing a serious limitation for its application in deep space exploration.

JPL first developed WVR. In 1995, Keihm conducted statistical analysis of one year of WVR data from Goldstone station in California compared with the station's prediction model, showing that neutral atmospheric correction precision could be improved by 30% on time scales within 1 hour, equivalent to prediction model precision beyond 1 hour [?]. In 2003, Tanner and Riley at JPL designed a new WVR installed at deep space stations to calibrate neutral atmospheric delay effects in Cassini spacecraft orbit determination. Through mutual comparison of two radiometers and nearly one year of continuous curve calibration, radiometer performance was evaluated. This WVR has brightness temperature

stability better than 0.01 K on 1000–10,000 s time scales, 0.05 K on 30-day time scales, and 0.15 K on one-year time scales [?]. In 2007, to support Cassini deep space exploration mission completion, narrow-beam gain-stabilized WVRs developed by JPL were equipped at DSN stations for high-precision calibration of neutral atmospheric fluctuations on 100–10,000 s time scales. Experiments showed that on short-baseline interferometry time scales of 2,000–10,000 s, the Allan standard deviation of wet delay calibration phase residuals is better than $2\langle MATH_{37} \rangle 10^{-15}$. Under semi-dry conditions, WVR can calibrate water vapor-induced relative delay to better than 1 mm (RMS) and absolute delay to better than 3 mm [?].

Each European deep space station is equipped with two sets of German-developed WVRs (model RPG-HATPRO). The first WVR was installed at the Spanish station in November 2014, 100 m from the deep space station radio telescope antenna to ensure minimal interference with the main antenna. This WVR consists of two receivers with 14 channels total: 7 channels measure the 20–30 GHz water vapor absorption band, and 7 channels measure the 50–60 GHz oxygen absorption band. This design provides better thermal stability and measurement precision. Research on WVRs (model RPG-ATPROP) installed at Cabauw in the Netherlands found that antenna beam speed has minimal impact on neutral atmospheric delay correction precision, with the optimal relative distance between radio antenna and WVR being 25 m and pointing deviations between the two antennas at the millimeter level [?].

In 2014, Graziani et al. [?] evaluated the role of WVR in calibrating neutral atmospheric variations in spacecraft orbit determination using Allan standard deviation (ASD). By introducing pointing offsets for WVR beams to intersect with deep space station antenna beams, distances between points in the wind volume decrease, reducing residual ASD. Tests showed ASD reduced to 55% of its zero-offset value. European deep space station WVRs show good consistency with ITU-R models [?] and nearby U.S. deep space station WVRs (10 km apart) [?], providing technical references for the European-Japanese BepiColombo Mercury exploration mission.

Around 2013, China's Kashgar and Jiamusi deep space stations each installed a WVR produced by the China Research Institute of Radiowave Propagation. In 2020, the Shanghai VLBI station was equipped with a German WVR (model RPG-G5), while Beijing, Kunming, and Urumqi VLBI stations were each equipped with a WVR (model HZD-X) produced by the China Research Institute of Radiowave Propagation, achieving long-term brightness temperature measurement precision of 0.2 K [?]. Compared with GNSS technology, the German RPG-G5 zenith wet delay correction precision is better than 10 mm, while the Chinese HZD-X zenith wet delay correction precision is better than 15 mm.

2.2.3 Other Methods Radiosonde data and numerical weather model (NWM) data can provide three-dimensional meteorological information, mak-

ing it possible to calculate atmospheric refractive index fields. Ray tracing technology integrates refractive index along the signal propagation path based on the refractive index field, directly obtaining atmospheric signal delay. Currently, multiple countries and regions can provide numerical weather forecast data, such as reanalysis data from the European Centre for Medium-Range Weather Forecasts and Climate Forecast System Reanalysis data from the U.S. National Centers for Environmental Prediction. Current NWM models incorporate more small-scale weather phenomena into model operations, ensuring precision in calculating neutral atmospheric delay through ray tracing even under extreme weather conditions. ZTD obtained through ray tracing compared with GPS-retrieved ZTD shows a bias of 0.9 mm and RMS of about 16 mm [?]. In EVN Venus detection missions, this method is used at low elevation angles or when spacecraft-radio source angular separation is large.

In 2016, Italian scholars proposed a method combining weather forecast numerical models with microphysical directional propagation schemes to predict atmospheric effects on Ka-band signals in deep space station links. Weather forecast numerical models predict short-term atmospheric states; microphysical directional propagation schemes are primarily three-dimensional radiative transfer models that calculate slant path attenuation and antenna noise temperature to predict Ka-band receiver signal-to-noise ratio. Compared with traditional ITU-R, this method can characterize thermal non-uniformity and atmospheric scattering. Using regional weather forecast numerical models for short-term atmospheric state prediction and selecting the BepiColombo spacecraft for testing, using daily rather than monthly climate statistics increased annual data return by over 20% in terms of short-term reception and data loss [?].

In 2021, considering systematic measurement errors and model stability, the Beijing Aerospace Flight Control Center improved the hybrid model for neutral atmospheric zenith delay and mapping functions, verified in Chang'e-5. The specific formula is:

$$\sin \theta + a + b$$

where D is neutral atmospheric delay, d , a , and b are model parameters, and θ is the observation elevation angle.

The neutral atmospheric delay hybrid model solves the problem of increasing errors at lower elevation angles, making modeling errors evenly distributed across the entire observation arc and improving neutral atmospheric delay model precision at low elevation arcs. RMS differences between model and measured values (including measurement equipment errors) at Jiamusi and Kashgar deep space stations are 0.165 m and 0.012 m, respectively [?].

Additionally, the International Earth Rotation and Reference Systems Service (IERS) specifications recommend corresponding correction methods for neutral atmospheric delay in radio and optical ground-based measurement data [?]. For

radio ground-based measurement data, the Saastamoinen model proposed by Davis et al. in 1985 is used as a priori value to correct neutral atmospheric delay, then the VMF1 mapping function model projects zenith delay to the slant path direction, with GMF used when VMF1 is unavailable. Neutral atmospheric wet delay and gradients are estimated as unknown parameters [?]. For optical ground-based measurement data, the neutral atmospheric zenith delay model proposed by Mendes and Pavlis in 2004 is recommended. Compared with ray tracing technology, this model has an RMS of 1 mm [?]. Then, the mapping function model proposed by Mendes et al. in 2002 projects zenith delay to the slant path direction. This mapping function model is based on Marini continued fraction representation, using one year of data from 180 global radiosonde stations to fit model coefficients [?].

2.3 Summary

This section introduced the mechanism and correction methods of neutral atmospheric delay. To more intuitively distinguish the advantages and disadvantages of various correction methods, Table 1 compares several commonly used neutral atmospheric delay correction methods in terms of timeliness, correction precision, and other aspects. Under real-time mission conditions, fitted zenith delay model + mapping function, microwave radiometer, and ray tracing technology can be used for correction, but the disadvantage of microwave radiometers is that they cannot be used in rainy weather. Since most numerical forecast models are built based on measured data from Europe and America, the correction precision of ray tracing technology based on numerical forecast models at Chinese deep space stations requires further verification.

Table 1 Comparison of Different Neutral Atmospheric Delay Correction Methods

| Method | Timeliness | Correction Precision | Measured Data Requirements |
|--|-----------------|---|----------------------------|
| Zenith delay model + mapping function | Quasi-real-time | Limited by numerical forecast model precision | Not required |
| Meteorological data + mapping function | Quasi-real-time | Hourly updated GNSS + mapping function | Required |

| Method | Timeliness | Correction Precision | Measured Data Requirements |
|--|----------------|----------------------|----------------------------|
| Post-processed GNSS + mapping function Ray tracing | Post-processed | Microwave radiometer | Cannot be used in rain |

Compared with various models, GNSS technology retrieval is a relatively high-precision method for correcting neutral atmospheric zenith delay. However, its disadvantage is that it cannot yet be used for real-time missions. Currently, GNSS tracking stations can provide real-time data streams, and the IGS Real-Time Working Group can provide real-time orbit and clock products, making real-time neutral atmospheric delay correction based on real-time data streams possible. This represents a future research direction for neutral atmospheric zenith delay correction in deep space exploration ground-based measurement data. Additionally, mapping function precision directly affects the level of neutral atmospheric delay correction for ground-based measurement data at low elevation angles. Currently, international GPT series models have relatively high correction precision and can be applied to real-time VLBI observation correction. Since current mapping function models are built based on global data while regional meteorological conditions vary significantly, in-depth research on localized mapping functions could be considered to further improve neutral atmospheric delay correction precision at low elevation angles.

3 Ionosphere

The ionosphere discussed in this paper primarily refers to the Earth's upper atmospheric region from 50 km to 1,000 km altitude, where considerable free electrons and ions exist, causing radio waves to change propagation speed and undergo refraction, reflection, and scattering.

3.1 Mechanism of Ionospheric Delay

The ionosphere exhibits non-uniformity, anisotropy, and dispersion. Non-uniformity manifests as varying electron density at different spatial positions, anisotropy shows refractive index varying with wave propagation direction, and dispersion means refractive index depends on wave frequency. When radio waves pass through the ionosphere, the refractive index is no longer equivalent to that in vacuum but is the ratio of light speed to wave propagation speed

in the ionosphere. This difference compared to vacuum propagation is called ionospheric delay.

The propagation path delay caused by electromagnetic waves passing through the ionosphere is:

$$\int (n \langle \text{MATH}_{38} \rangle 1) ds + ds \langle \text{MATH}_{39} \rangle$$

where ds represents the true propagation path from signal to observation station, and dr represents the geometric propagation path. The second factor represents the degree of bending between geometric and propagation paths.

Charged particle distribution in the ionosphere is extremely non-uniform. Ionospheric delay magnitude depends on spacecraft line-of-sight, observation frequency, time of day, season, and time since the current solar cycle began. At S-band, zenith ionospheric delay ranges from 1–10 m, with delay at approximately 0° elevation being about 3.5 times the zenith delay.

When using VLBI technology for spacecraft tracking, alternating observations of spacecraft and extragalactic radio sources can eliminate station-related errors. Meanwhile, angular separation between spacecraft and extragalactic radio sources affects differential errors—larger angular separation leads to larger differential errors. Ionospheric delay error on differential observations can be expressed as:

$$\Delta \tau_{ion} \langle \text{MATH}_{40} \rangle 2 \langle \text{MATH}_{41} \rangle \varepsilon_{ion} \langle \text{MATH}_{42} \rangle f_m \langle \text{MATH}_{43} \rangle \theta_{sep}$$

where ε_{ion} is the error after ionospheric delay correction in any direction, f_m is the derivative value of the mapping function, and θ_{sep} is the angular separation of the spacecraft relative to the extragalactic radio source.

3.2 Ionospheric Delay Correction Methods

Ionospheric delay errors are related to observation frequency, reaching tens of nanoseconds at 2 GHz. Ionospheric delay is inversely proportional to the square of observation frequency. According to frequency differences, ionospheric delay error correction methods are commonly divided into dual-frequency observation and single-frequency observation methods.

3.2.1 Dual-Frequency Observation Ionospheric Delay Error Correction Method Assuming deep space stations observe the spacecraft at two frequencies f_1 and f_2 , the radio signal path delay caused by the ionosphere is:

$$\Delta \rho_{ion}(f_1) = \Delta \rho_{ion}(f_2) = \langle \text{MATH}_{44} \rangle CTE \langle \text{MATH}_{45} \rangle$$

where $\Delta\rho_{ion}$ is the signal delay caused by the ionosphere, $k_1 = 40.28 \text{ m}^3 \langle MATH_{46} \rangle \text{s}^{-2}$, and CTE is the total electron content along the electromagnetic wave propagation path.

The time difference for signals at the two frequencies arriving at the station is:

$$t_2 \langle MATH_{47} \rangle t_1 = k_1 \langle MATH_{48} \rangle CTE \langle MATH_{49} \rangle$$

Then the ionospheric delay for the two radio frequency signals arriving at the station can be obtained as:

$$\Delta t_{ion}(f_1) = \Delta t_{ion}(f_2) = \langle MATH_{50} \rangle \frac{f^2 \langle MATH_{51} \rangle f^2}{(t_2 \langle MATH_{52} \rangle t_1)}$$

The IERS specifications recommend using this method to correct ionospheric delay effects during dual-frequency observations [?]. For deep space exploration ground-based measurement data, this method can eliminate first-order ionospheric effects, with residual higher-order effects on group delay being less than 1 mm and negligible. The U.S. Cassini spacecraft first used multi-frequency links (Ka and X bands) to eliminate Earth's ionospheric effects [?].

For most deep space exploration VLBI orbit determination missions, the single-channel bandwidth and total frequency band span cannot be as wide as geodetic VLBI technology, and real-time missions cannot guarantee that all spacecraft observation beacons are active, making the dual-frequency method unsuitable for real-time ionospheric effect elimination.

3.2.2 Single-Frequency Observation Ionospheric Delay Error Correction Method For single-frequency radio signal observations, ionospheric delay errors can be corrected through models. Since ionospheric delay is frequency-dependent, correction must distinguish station, spacecraft, and frequency.

(1) U.S. Spacecraft Ionospheric Delay Correction Method

In 1986, Lanyi used GPS satellite observation data to construct a regional ionospheric correction model using polynomial expressions, opening a new direction for ionospheric model retrieval using GNSS data [?]. In 2001, during U.S. Mars Odyssey spacecraft orbit determination using deep space station Δ DOR measurement data, ionospheric delay was corrected using an ionospheric correction model retrieved from GPS observation data. Since the Madrid deep space station had no observation data, differential range and integrated Doppler technology were used to determine total electron content [?]. In 2007, JPL used ionospheric correction models retrieved from GPS observation data to calibrate deep space station Δ DOR, VLBI observations, and VLBA array observations [?]. From 2006 to 2009, during U.S. Cassini spacecraft Venus detection using 10 VLBA antennas for tracking, ionospheric delay was corrected using vertical

total electron content (VTEC) global distribution maps retrieved from GPS observation data, with 2-hour VTEC sampling intervals and linear interpolation to calculate VTEC at tracking stations [?].

U.S. deep space exploration ionospheric delay correction is designed for each tracking station, spacecraft, and frequency. Ionospheric calibration delay values use 2,295 MHz as the reference frequency, which can be easily converted to other frequencies according to mission requirements, calculating ionospheric calibration delay for each tracking station's spacecraft line-of-sight. Ionospheric calibration delay is expressed as normalized polynomials as a function of normalized time, providing multiple piecewise continuous polynomials simultaneously. Users must provide spacecraft orbit information, and for Δ DOR measurement data, extragalactic radio source position information is also required [?].

(2) European Spacecraft Ionospheric Delay Correction Method

The European Deep Space Network primarily used the Klobuchar model for ionospheric delay correction in early stages [?], with 50% correction precision. Since the 21st century, another empirical model NTCM-GL (Global Neustrelitz TEC Model) has been developed [?]. This model is fitted based on high-precision global total electron content (TEC) data from 1998–2007 provided by the Center for Orbit Determination in Europe (CODE), with a negative bias of 0.3 TECU and RMS bias of 7.5 TECU. Compared with TOPEX/Poseidon altimeter results, NTCM-GL model RMS bias is 5 TECU and 11 TECU during low and high solar activity years, respectively. Based on cooperation agreements, European Deep Space Network ionospheric delay correction is also technically supported by JPL.

In recent years, in addition to the neutral atmospheric delay correction platform, the European Deep Space Network has developed an independent ionospheric delay correction platform. This platform calculates ionospheric delay based on GNSS observation data by the European navigation office. The platform relies on internal data and software as much as possible, being simple, reliable, and easy to operate, using the NTCM-GL model as the background field. Required inputs and processing strategies include: (1) GNSS observation data from European tracking stations and global IGS network observation data; (2) conventional GNSS satellite orbit and clock products, conventional slant total electron content (sTEC), and differential code bias (DCB) published by IGS; (3) specified 48-hour interval European spacecraft/quasar trajectory information; (4) since each European Deep Space Network observation does not exceed 15 hours, daily ionospheric calibration values cover 48 hours from 0:00 of the previous day to 0:00 of the current day, automatically running daily at 7:33; (5) observations are only considered when station cutoff elevation angle $> 5^\circ$; (6) like neutral atmospheric calibration, fast and final modes are distinguished, with the final mode starting at the same time daily but with a 4-day delay; (7) when GNSS observation data is unavailable, the European Deep Space Network uses NTCM-GL to calculate ionospheric delay.

GNSS receiver and satellite DCB are obtained from daily global ionospheric model estimation runs by the navigation office. DCB cannot be estimated in an absolute sense, achieved by specifying a reference where the sum of satellite DCBs is zero. To avoid significant day-to-day variations in DCB estimates, such as changes in the average due to satellite loss on a given day, daily DCB estimates from the past 7 days are combined.

Since spacecraft observation frequencies differ, ionospheric delay conversion between different frequencies is performed through the following formula:

$$g_{ion} = +40.3 \langle MATH_{53} \rangle sCTE$$

where f is frequency and g_{ion} is ionospheric delay at frequency f , with $f = 2,295 \langle MATH_{54} \rangle 10^6$ Hz set during calculation.

Additionally, during European Smart-1 probe phase, U.S. Mars Rover B cruise phase, and Cassini probe position at Saturn, EVN was used for tracking. In VLBI data processing, ionospheric delay errors were corrected using 2-hour sampled VTEC grid files provided by IGS and a single-layer projection function, with CVTE precision of 2–9 TECU [?]. The specific calculation formula is:

$$CTE = \frac{CVTE}{\cos(z')}$$

where CTE is slant total electron content in the observation direction, $CVTE$ is vertical total electron content, and z' is the zenith distance from the ionospheric single-layer model to the target spacecraft.

$$z' = \arcsin \left(\langle MATH_{55} \rangle \frac{\sin(z)}{R + H} \right)$$

where R is Earth's mean radius, H is ionospheric height, and z is the apparent vacuum zenith distance of the target spacecraft.

Ionospheric delay at each station can be calculated as:

$$\tau_{ion} = \frac{5.308018 \langle MATH_{56} \rangle CTE}{4\pi^2 \langle MATH_{57} \rangle f^2}$$

where f is observation frequency.

(3) Japanese Spacecraft Ionospheric Delay Correction Method

Since 2001, Japan has used multi-frequency VLBI technology for SELENE spacecraft orbit determination, eliminating first-order ionospheric delay effects

through dual-frequency observations. When spacecraft frequency changes prevent dual-frequency combination elimination, the CODE-provided global ionospheric CTE model is used for correction. This ionospheric model is constructed based on retrieval from global GNSS network observation data, represented by 15th-order spherical harmonic coefficients with 2-hour time resolution, obtaining 1-minute sampled ionospheric correction data through smoothing interpolation [?].

(4) Chinese Spacecraft Ionospheric Delay Correction Method

The Beijing Aerospace Flight Control Center researched and validated an ionospheric delay correction method for real-time interferometric measurement of S-band beacon signals for Chang'e-4 relay satellite missions, combining the sparse calibration working mode used by deep space tracking interferometric measurement systems. The specific strategy includes: (1) based on about 3 days of deep space station CTE measured data before the tracking arc; (2) since TEC provided by GPS dual-frequency receivers configured at stations is line-of-sight measured values, first converted to zenith CVTE values according to ionospheric projection function, selecting trigonometric function-type projection functions; (3) quality assessment of continuous CVTE sequences, eliminating abnormal time period observations, fitting polynomial models based on daily characteristics with day-of-year seconds as independent variable and CVTE as variable, with model order dynamically adjustable based on fitting residuals; (4) calculating station CVTE values based on model coefficients and day-of-year seconds within the tracking arc; (5) combining target elevation angle information within the tracking arc from the data processing system, converting through projection functions to calculate line-of-sight CTE predicted values. Through analysis of measured data during Chang'e-4 relay satellite mission, this method can improve real-time measurement precision by 1–3 ns, with more obvious advantages for low-elevation tracking arcs [?].

Since the IGS tracking network has wide coverage with large inter-station distances, the Shanghai Astronomical Observatory CVN of the Chinese Academy of Sciences adopted China's "Crustal Movement Observation Network of China" densification approach to construct the global ionospheric precise correction model SHAO-GIM, solving the problem of sparse IGS tracking network in China and improving ionospheric delay correction precision at Chinese CVN stations. Figure 4 [Figure 4: see original paper] shows VLBI orbit determination residuals in 6 baseline directions at CVN stations after ionospheric delay correction using CODE and SHAO GIM models in S1 band during Chang'e-5 reentry return flight test on October 24, 2014. Using Chang'e-5 reentry return flight test measured data for analysis and comparing with CODE's global ionospheric model products, VLBI orbit determination residuals based on SHAO-GIM decreased from 6.07 ns to 3.33 ns in S1 band, from 9.10 ns to 7.07 ns in S2 band, and from 0.70 ns to 0.60 ns in X0 band [?].

Additionally, IERS specifications also recommend using CVTE models combined with mapping functions to correct ionospheric delay effects. For post-

processing users, IGS-provided global grid CVTE models can be used, with correction errors of 10%–20%. For real-time users, CODE-provided global VTEC prediction models can be used, with average correction errors of about 50% [?].

3.2.3 Ionospheric Delay Error Correction Empirical Models Ionospheric delay in ground-based measurement data can also be corrected through some empirical models. IERS specifications recommend using the International Reference Ionosphere (IRI) model, Klobuchar model, NeQuick model, or PIM empirical model [?]. The advantage of empirical models is their applicability to real-time deep space exploration missions, but their disadvantage is low correction precision. For example, the IRI model incorporates ionosonde, incoherent scatter radar, satellite, and rocket sounding data, with correction effectiveness of 50% [?]. Additionally, the NTCM-GL background field model used in European deep space exploration mentioned in Section 3.1 is also an empirical model.

3.3 Summary

This section introduced the mechanism and several commonly used correction methods for ionospheric delay. To more intuitively distinguish differences between commonly used ionospheric delay correction methods, Table 2 compares them in terms of timeliness, correction precision, and observation frequency requirements. For real-time single-frequency observations, empirical models or global VTEC prediction models + mapping functions are recommended; for post-processing missions, global VTEC post-processing models + mapping function combinations are recommended; for deep space exploration missions with dual-frequency observations, dual-frequency combination methods can be used to correct ionospheric delay effects.

Table 2 Comparison of Commonly Used Ionospheric Delay Correction Methods

| Method | Timeliness | Correction Precision | Observation Frequency Requirements |
|--|----------------|-----------------------------|------------------------------------|
| Dual-frequency combination | Real-time | Eliminates first-order term | Dual-frequency and above |
| Global VTEC post-processing model + mapping function | Post-processed | Single-frequency and above | |

| Method | Timeliness | Correction Precision | Observation Frequency Requirements |
|---|------------|----------------------------|------------------------------------|
| Global VTEC prediction model + mapping function | Real-time | Single-frequency and above | |
| Klobuchar model | Real-time | Single-frequency and above | |
| NTCM-GL model | Real-time | Single-frequency and above | |
| NeQuick model | Real-time | Single-frequency and above | |
| IRI model | Real-time | Single-frequency and above | |

In recent years, IGS has begun providing global real-time ionospheric products using 15th-order spherical harmonic functions with 20-minute time resolution. Compared with final global ionospheric model products, precision is about 3 TECU [?], representing a current research hotspot. With continuous deepening of ionospheric research, hourly-updated and real-time global ionospheric model products have been developed and are expected to be applied to deep space exploration missions, improving ionospheric delay correction precision and timeliness.

4 Solar Plasma

Spacecraft flying in interplanetary space are strongly affected by solar wind. Solar wind is the result of high-density, strong-turbulence ionized gas (plasma) ejected from the Sun. These ionized ions flow from the Sun at 400 km/s, diffusing into vast interplanetary space and making interplanetary space a plasma region [?]. When electromagnetic waves pass through these regions, communication signals experience time delays of up to tens of meters.

Solar plasma delay errors are typically estimated using empirical models. In 1981, Muhleman and Anderson proposed the M&A electron density model [?], which can well reflect the physical background of plasma regions and is widely used in engineering missions. The solar distance correction formula provided by NASA uses the M&A model. Plasma density in this model can be approximately expressed as:

$$N_e(r, \phi) = r^{2.7} \exp\left(\langle MATH_{58} \rangle \frac{\phi^2}{\phi_s^2}\right)$$

where r is the radial distance from the Sun center to the line connecting the spacecraft and telescope (in solar radii); ϕ is the heliographic latitude at that point, i.e., the angle between the point-Sun center line and the solar equatorial plane; ϕ_s is the heliographic latitude corresponding to maximum plasma density at the same heliocentric distance; D and B are model coefficients fitted from observation data. Muhleman and Anderson derived electron density for the 1976 solar minimum using measurement data from the Viking spacecraft on Mars, taking $D = 1.32\langle MATH_{59} \rangle 10^6$ and $B = 2.3\langle MATH_{60} \rangle 10^5$.

In 1995, Bird et al. [?] inverted and established the Bird model based on Ulysses spacecraft dual-frequency signals. In 2010, California Institute of Technology researchers proposed the Caltech model [?], applicable to low heliographic latitude regions and only related to target distance from the Sun center, with simple operational logic. The model formula is:

$$N_e(r) = 2.21\langle MATH_{61} \rangle 10^{14} + 1.55\langle MATH_{62} \rangle 10^{12} \left(\frac{a}{R_0}\right)^{-2.3}$$

where $N_e(r)$ is plasma density, a is the radial distance from Sun center to the line connecting spacecraft and telescope (in meters), and R_0 is solar radius ($R_0 = 6.96\langle MATH_{63} \rangle 10^8$ m). Figure 5 [Figure 5: see original paper] shows the geometric relationship for calculating solar plasma using the Caltech model.

Liu Qinghui et al. [?] simulated and analyzed plasma delay effects when using VLBI technology for Tianwen-1 orbit determination, calculating based on Sun-Earth-spacecraft angle variations during Tianwen-1 launch to landing, finding solar plasma delay relatively small. The Beijing Aerospace Flight Control Center analyzed Tianwen-1 solar plasma delay errors using both Caltech and M&A models, showing comparable precision between the two models. Figure 6 [Figure 6: see original paper] shows the two-way impact error of plasma delay on UXB ranging at Jiamusi, Kashgar, and Argentine deep space stations during Tianwen-1 detection, with a maximum of about 18.6 m. Plasma effects must be considered when using ranging and Doppler data for orbit determination [?].

5 Summary and Outlook

In deep space exploration spacecraft orbit determination, propagation medium errors are an important error source, mainly including neutral atmospheric delay errors and ionospheric delay errors. To effectively reduce the impact of this error source, appropriate neutral atmospheric and ionospheric delay correction methods must be selected according to timeliness differences. Therefore, we have analyzed in detail the mechanisms of neutral atmospheric and ionospheric

delay errors and correction methods at various tracking stations, mainly including those of the United States, European Union, Japan, and China. Russia has relatively few exploration missions in the past 30 years, with limited publicly available information. For neutral atmospheric delay errors, zenith delay + mapping function models and WVR-based correction methods can typically be used. If spacecraft have dual-frequency signal observations, dual-frequency combination can eliminate general ionospheric effects, with higher-order effects being small and negligible. However, most spacecraft use single-frequency signal observations, where global or regional ionospheric models can be used for correction. Additionally, for interplanetary exploration affected by plasma, we briefly introduced commonly used plasma error correction methods.

With continuous deepening of deep space exploration, requirements for spacecraft orbit determination precision are increasing. Due to neutral atmospheric delay effects, low-elevation orbit determination delay residuals remain large, representing a major factor constraining spacecraft orbit determination precision improvement. Currently, globally universal mapping function models are used, but meteorological conditions vary significantly across stations. Therefore, constructing localized mapping function models for deep space stations is a future research focus and an international research hotspot and challenge.

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