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Research Article

Improving the Accuracy of the Martian Ephemeris Short-Term Prediction

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The Chinese Mars exploration mission is planned to be launched in 2020, which includes an orbiter, a lander, and a rover. High precision Martian ephemeris is very important in Mars exploration, especially for the Martian orbit insertion and the Martian lander/rover landing. In this paper, we used simulation data to analyze the short-term prediction accuracy of the Martian ephemeris. The simulation results show that the accuracy of Mars position is expected to be better than 50 m for 180-day prediction, when 90-150 days' range measurements are used to estimate the orbit of the Mars. Range bias affects the prediction accuracy and the arc length for estimation is limited. The prediction accuracy will improve with higher orbit, and the orbit error of probes has an obvious effect on the prediction accuracy of the Martian ephemeris.

1. Introduction

The Chinese Mars exploration mission is planned to be launched in 2020, which includes an orbiter, a lander, and a rover [1]. The orbiter will conduct global surveys of Mars and produce maps of the Martian surface topography as well as other scientific data; moreover, the lander carrying the rover is going to perform chemical analyses on the soil and look for biomolecules and biosignatures. Precise orbit determination and prediction of the relative position between the probe and the target object plays an important role in deep space navigation. Based on the experience accumulated through early Mars exploration missions, most of the subsequent missions have been performed successfully. Planetary spacecraft navigation is becoming more and more complicated, requiring higher accuracy. After several months of the Earth-Mars transfer orbit flight, any material mistake in the Martian orbit insertion and the landing progress may cause the spacecraft to be not placed at an optimal position and then miss the planet or have a crash landing on the surface of Mars. Accurate navigation allows the immediate entry of a spacecraft into a planet's atmosphere, which requires an extremely accurate entry angle, thereby taking advantage of aerobraking and avoiding the fuel-consuming process of orbit insertion.

The uncertainty of the planetary ephemerides is one of the major factors that affect the accuracy of the navigation. Jet Propulsion Laboratory (JPL) has been continuously supporting the maintenance and improvement of the ephemerides since the 1960s to satisfy the needs of high precision planetary ephemeris for the deep space navigation. For the Viking mission in 1976, the ephemeris accuracy requirements for Mars orbit insertion were on the level of 50 km; in the same period, the ephemeris accuracy requirements were raised to 5 km for the Pathfinder probe, which was required for a direct entry into the Mars atmosphere. For Mars Exploration Rover (MER), which was launched in 2003, the demand was better than 1km [2]. For Mars Science Laboratory (MSL), two series of Jet Propulsion Laboratory Development Ephemeris (JPL DE) were used: DE424 [3] and DE425 [4]. DE424 was generated two months before launch. It was expected that the position error between the Mars and the Earth at the time of insertion of MSL was less than 10 m in the line of sight, 125 m in right ascension, and 225 m in declination. In order to reduce the uncertainly of the Martian ephemeris, the Delta Differential One-way Ranging (ΔDOR) measurements of Mars Reconnaissance Orbiter (MRO) and Odyssey (ODY), as well as the range measurements, were used to generate DE425 ephemerides three months before arrival to Mars [5], and the Mars-Earth relative position error was about 10 m in the line of sight, 100 m in right ascension, and 150 m in declination [6].

The data of Mars Global Surveyor (MGS) and Mars Express (MEX) were also used for the JPL DE [7, 8]. Odyssey, MGS, and MRO were in polar orbits of small-eccentricity. Odyssey began mapping in a (390×455) km orbit (about 20 km higher than MGS) and MRO spacecraft provided tracking data in a (255×320) km altitude orbit. The typical total orbit overlap errors of the three spacecraft are about 1 m. The radial, along-track, and normal average orbit errors of MGS or Odyssey were 15 cm, 1.5 m, and 1.6 m, respectively [9]. Due to the improved modeling, average overlap errors of MGS reduce to 12 cm, 0.9 m, and 0.9 m, and those of MRO reach 4 cm, 0.6 m, and 0.5 m [10]. Mars Express (MEX), which reached Mars in December 2003, was the first Mars probe of European Space Agency (ESA). It is a large eccentricity orbiting satellite with peri-Martian height of about 300 km and apomartian height of more than ten thousand kilometers [11]. The root mean square (RMS) of MEX position differences between successive 7 days' data arcs over overlap duration of 21h has been calculated by Royal Observatory of Belgium (ROB). The average accuracy of the orbits has been estimated to be around 20-25 m [12].

According to the time and coordinates system standard for the Chinese Mars exploration mission, DE421 ephemeris, which was released in 2008, will be adopted in this mission. DE421 included additional ranging and Very Long Baseline Interferometry (VLBI) measurements of Mars spacecraft and Venus Express spacecraft, the updated estimates of planetary masses, additional lunar laser ranging, and so on, and the Mars position accuracy predicted to 2008 was expected to be better than 300 m [7]; moreover, because of the perturbations by asteroids, the accuracy was expected to be lower. It is a great challenge for China to accomplish 'orbiting, landing, and patrolling' in the first Mars exploration mission in 2020. High precision Martian ephemeris can be used to improve the orbit determination and controlling accuracy of the crucial arcs, such as trajectory correction maneuvers (TCM) and Mars landing [13], and reduce failure probability of mission. In this paper, a method of improving the accuracy of the short-term prediction of the Martian ephemeris is proposed; furthermore, accuracy of the short-term prediction of the Martian ephemeris is analyzed and discussed through orbit simulation. The related ephemeris products can be used in the engineering and scientific application of the Chinese Mars exploration.

2. Strategy for Short-Time Prediction of the Martian Ephemeris

Updating ephemeris is necessary for meeting the requirements of Mars exploration. Taking the DE430 ephemeris as an example, which was released in 2013, 5 years after

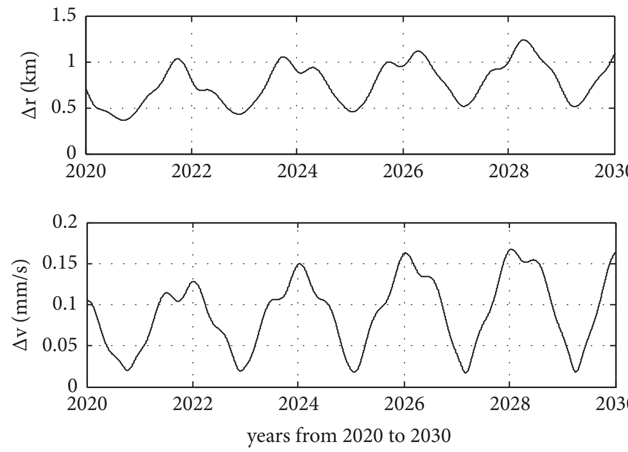

Figure 1: The difference on relative positions and velocities of Mars and earth between DE421 and DE430.

DE421, the Mars orbit has been improved through an updated treatment of asteroids and additional VLBI observations and range measurements [8]. Figure 1 shows the period from 2020 to 2030, and the difference on relative positions and velocities of Mars and earth between DE421 and DE430 ephemerides will be about 1 km and 0.2 mm/s. Thus, when China launches the Mars probe in 2020, the error in Mars orbit in DE421 will increase from 300 m to about 1 km.

The range/Doppler and VLBI techniques are used in Chinese deep space explorations. Chinese Deep Space Network (CDSN) includes Jiamusi (JMS), Kashgar (KS), and Zapala (ZP, Argentina) deep space stations. Chinese VLBI network (CVN) consists of Tianma, Beijing, Kunming, and Urumqi. Since it is different for the sensitivity of different types of measurements to the error of ephemerides, Martian ephemeris should be improved by using the most sensitive measurement data in principle.

The Chinese Mars probe will enter the 7.2 hours period mission orbit to perform remote studies of Mars. The differences of the simulated measurements using different ephemerides (DE421 and DE430) are shown in Figure 2. The results indicate that the difference for range data (JMS station) is about 38.5m and 0.005mm/s, 0.005ns, and 0.001ps/s for Doppler, VLBI delay, and rate, respectively.

The accuracy of range measurement is better than 1m, Doppler measurement is about 0.1mm/s, delay measurement is 0.1ns (phase delay is 10ps), and delay-rate measurement is 1ps/s. Comparing with the results shown in Figure 2, we can conclude that the Doppler, delay, and delay-rate measurements now cannot distinguish the differences between DE421 and DE430 clearly. For that reason, range measurements were used to estimate the Mars orbit, while the Doppler data could be used to determine the orbit of the spacecraft. In this paper, the orbit determination of Mars and the spacecraft flying around Mars were independent.

The orbit of the spacecraft was determined firstly, and the spacecraft orbit was fixed to determine the Mars orbit. Some researchers have processed the tracking data of MEX and analyzed the orbit determination accuracy. The tracking

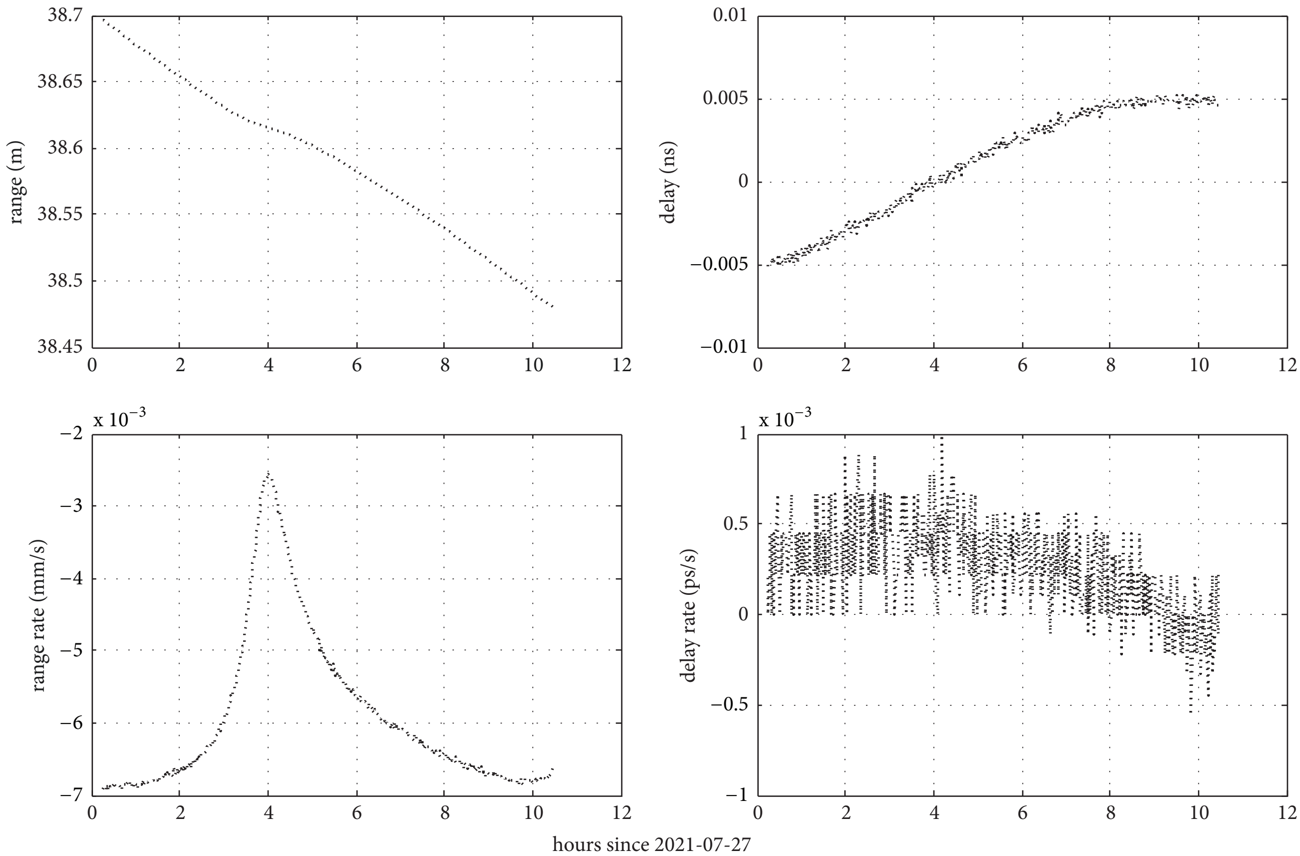

Figure 2: Measurement differences using DE421 and DE430.

measurements were two-way and three-way Doppler in the S- and X-bands. Three CVN stations located at Shanghai, Kunming, and Urumqi started tracking MEX on August 7, 2009, and the tracking lasted about 8 hours. In the MEX observations, the transmitting station was New Norcia (NNO) station in Australia belonging to the ESA. The X-band uplink signals were generated from NNO station and X/S-band downlink signals were retransmitted after frequency multiplication by an on-board transponder [14]. Yan et al. used Mars Gravity Recovery and Analysis Software (MAGREAS) to process the MEX tracking data with two-way and three-way tracking modes separately. The postfit residuals RMS of two-way Doppler were about 0.067 mm/s and the ones of two-way Doppler were about 0.079 mm/s. The orbits were compared with the orbit results from ROB, and the maximum position error was less than 8 m for two-way Doppler and less than 100 m for three-way Doppler [15]. Ye et al. used Wuhan University Deep Space Orbit Determination and Gravity Recovery System (WUDOGS) for MEX precision orbit determination (POD) with two-way Doppler, and the reconstructed orbit differences between WUDOGS and ROB are on 25 m level for position and less than 10 mm/s for velocity [16, 17].

We also used the software developed by Shanghai Astronomical Observatory (SHAO) named Shao Orbit Determination Program (SODP) to determine the orbit of the MEX. Table 1 gives the MEX orbital tracking data and Table 2 gives the force models in MEX's POD. Analysis of the orbit differences between the solved orbit and ROB's reconstructed orbit is presented in Table 3.

Table 1: MEX orbital tracking data.

Types of tracking data	Observation time	Stations
Two-way Doppler	From 2009-08-07T20:40 to 2009-08-08T04:00(UTC)	NNO-NNO
Three-way Doppler		NNO-Shanghai, NNO-Kunming, NNO-Urumqi

Table 2: The configuration of SODP in MEX POD.

Item	
Martian gravity field	GMM3_120
N-body perturbation	Sun, planets, Moon, Phobos, and Deimos
Solar radiation	Fixed ratio of area to mass
Relativity perturbation	Schwarzschild
Initial coordinate	Mars J2000
Mars-centered coordinate	Pathfinder model
Earth tropospheric correction	Hopfield model

Table 3: The reconstructed orbit differences between SODP and ROB.

Types of tracking data	Position (m)				Velocity (m/s)			
	R	T	N	Pos.	R	T	N	Vel.
Three-way Doppler	1.11	50.20	23.31	55.36	0.008	0.004	0.007	0.011
Two-way & three-way Doppler	1.06	18.98	9.24	21.13	0.003	0.002	0.003	0.004

The postfit RMS of residuals was about 0.15mm/s, and the position and velocity differences between SODP and ROB were about tens of meters and about 0.01 m/s, respectively.

Mars orbit can be determined using range measurements with long data arcs to improve its accuracy while keeping the orbit of the spacecraft fixed. Besides measurement error, the probe orbit error is one of the main error sources in the process of Mars orbit determination.

Given a more rigorous equation of motion, Mars orbit integration needs to be performed in the framework of general relativity that is different from the framework of Newtonian physics, in which the motion of an earth satellite is considered. In the weak gravitational field of the solar system, the motion of Mars under the influence of the forces of the sun and the planets is described as

$$\begin{aligned}\ddot{\vec{r}} ={}& \sum_j \frac{\mu_j\left(\vec{r}_j-\vec{r}\right)}{r_{sj}^3} + \sum_j \frac{\mu_j\left(\vec{r}_j-\vec{r}\right)}{r_{sj}^3}\left\{-\frac{2\left(\beta+\gamma\right)}{c^2}\right.\\ &\cdot\sum_k \frac{\mu_k}{r_{sk}} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} + \gamma\left(\frac{v}{c}\right)^2 + \left(1+\gamma\right)\left(\frac{v_j}{c}\right)^2\\ &\left.-\frac{3}{2c^2}\left[\frac{\left(\vec{r}_j-\vec{r}\right)\cdot\dot{\vec{r}}_j}{r_{ij}}\right]^2 + \frac{1}{2c^2}\left(\vec{r}_j-\vec{r}_i\right)\cdot\ddot{\vec{r}}_j\right\} \qquad (1)\\ &+\frac{1}{c^2}\sum_j \mu_j \frac{\left(\dot{\vec{r}}_j-\dot{\vec{r}}\right)}{r_{sj}^3}\left\{\left[\vec{r}_j-\vec{r}\right]\right.\\ &\left.\cdot\left[\left(2+2\gamma\right)\dot{\vec{r}}-\left(1+2\gamma\right)\dot{\vec{r}}_j\right]\right\} + \frac{\left(3+4\gamma\right)}{2c^2}\sum_j\frac{\mu_j\ddot{\vec{r}}_j}{r_{sj}}\end{aligned}$$

where β and γ, which are used as the general relativity (GR) value 1, are post-Newtonian (PN) parameters, c is the speed of light in vacuum, $\vec{r}$ is the position vector of Mars in the Barycentric Celestial Reference System (BCRS), v is the norm of velocity vector, μ_j is the gravitational constant of each body, $\vec{r}_j$ is the position vector of each body in the BCRS, and r_{sj} is distance from the jth body to Mars. The formula is Newtonian equation of motion, which is the first term, with additional post-Newtonian correction terms.

In this paper, simulation data was used to analyze the accuracy of improved short-term Martian ephemeris. The work flow of this simulation is as follows:

(1) Propagate a Mars orbit according to the initial state derived from the DE421 ephemeris to get the "true" Mars ephemeris.

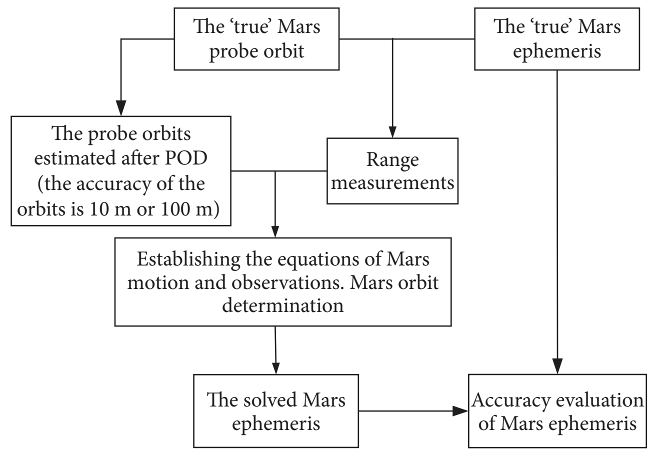

Figure 3: The flowchart of the Mars ephemeris determination.

(2) Simulate range data with noise and bias according to the "true" Mars ephemeris and the "true" Mars probe orbit.

(3) Estimate the Mars orbit and analyze the Mars ephemeris accuracy. The orbit of the probe was fixed and obtained from POD results with the orbital errors.

Various probe orbits with certain errors obtained under different trajectory determination strategies were used to perform Mars OD by Monte Carlo method, in which the measurement noise was produced at random on a certain level of precision. According to the above sensitivity analysis, for spacecraft in orbit around Mars, the Doppler measurements were used to estimate the orbit of the spacecraft and range measurements were then used to improve the Mars ephemeris. The detailed flowchart is as in Figure 3.

In our simulation, the tracking stations were JMS, KS, and ZP. The measurement noise of range rate data was 0.1mm/s and that of the range was 1m. The measurement sampling interval was 30s. The influence of the length of data arc, observing strategy, range bias, spacecraft's orbit accuracy, spacecraft's orbit altitude, and spacecraft's orbit inclination on short-time prediction accuracy of the Mars orbit was analyzed. The specific analysis scheme is as in Table 4.

3. Simulation Analyses

Since the Mars velocity accuracy of JPL ephemerides is better than 0.2mm/s and it is much higher than that of Mars probe, which is about 10 mm/s, we constrained the initial velocity vectors and only estimated position components of Mars in the simulation analysis, and the initial position error of the

Table 4: Factors affecting the short-term prediction of the Martian ephemeris.

Factors		Scheme
Data arcs(days)		0/30/60/90/120/150/180/210
Observing strategy	Stations Frequency	KS, JMS and ZP; JMS and ZP Every day/Every 5 days
Range bias		5 m/ 0 m
Orbit accuracy of a probe		10 m/ 100 m
Orbit altitude of a probe		200 km/ 5000 km
Orbit inclination of a probe		0°/30°/60°/90°

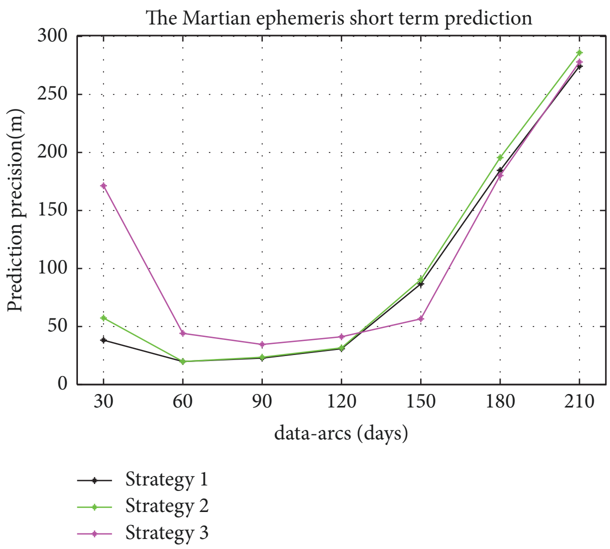

Figure 4: The Martian ephemeris short-term prediction under different observing strategies.

Mars was 1km; furthermore, the calculation results of this paper were based on Monte Carlo simulations.

3.1. The Influence of Tracking Stations and Observing Frequency. For the (200×200) km Mars probe orbit—with orbital inclination of 0° and orbit error of 10 m—three observing strategies shown in Table 5 were adopted to estimate the Mars orbit.

Mars orbit was determined using 30, 60, 90, 120, 150, 180, and 210 days' observations and predicted to 180 days, and the prediction results are shown in Figure 4. For Strategy 1 and Strategy 2, the prediction accuracy was about 50 m using 30 days' data arc, and it was better than 50 m using 60, 90, and 120 days' data arcs. It was decreased when data arc was longer than 120 days, and it was about 300 m using 210 days' data arc. Compared to Strategy 1 and Strategy 2, the accuracy was lower for Strategy 3, which was about 200 m using 30 days' data arc and about 50 m using 60, 90, 120, and 150 days' data arcs.

It can be concluded that with the accumulation of the observation arc length, the accuracy of the orbit prediction of these three strategies is on the same level. This is mainly

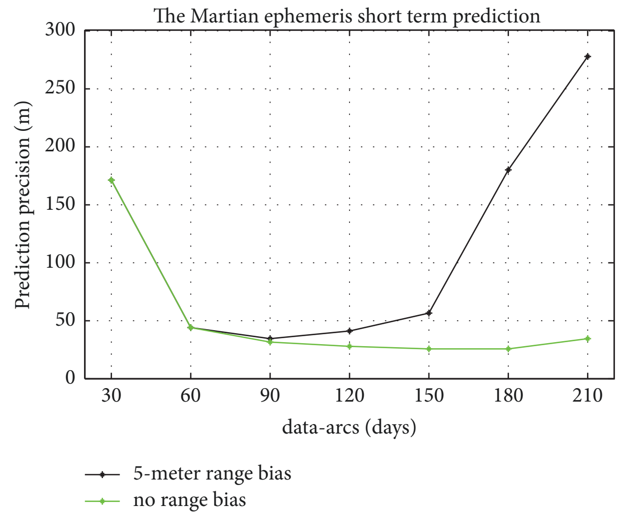

Figure 5: The Martian ephemeris short-term prediction using data whether containing range bias.

because the requirement for the number and frequency of the observation is reduced when the observation arc is long enough. Considering the ground stations resource is limited, the following analyses on influence of range bias, spacecraft's orbit accuracy, altitude, and inclination on short-time prediction accuracy of the Mars orbit were based on Strategy 3.

3.2. The Influence of Measurement Systematic Errors. This section analyses the influence of different ranging systematic errors on the short-term predication accuracy of the Mars position. For the (200×200) km Mars probe orbit—with orbital inclination of 0° and orbit error of 10 m—considering the error of 0 m/5 m ranging systematic respectively, we used 30/60/90/120/150/180/210 days' data arc to determine the position of Mars and forecast for 180 days, and the results are shown in Figure 5.

It can be concluded that when the observation arc was less than 90 days, the 0 m/5 m ranging systematic error had little influence on the accuracy of the Mars position prediction. However, with the increase of the observation arc length, the prediction accuracy using the observations which included 5 m ranging systematic error was obviously decreased, while the result using the observations without ranging systematic error was stable on the level of about 40 m. This is mainly because the ranging systematic error is accumulated with the increase of the observation arc length, resulting in influencing the orbit determination accuracy of the Mars position.

According to the above analysis, consider that the ranging systematic error cannot be avoided in deep space mission; moreover, the results of using observations without ranging systematic error of 120/150/180/210 days' data arc are on the same level. So the observations containing 5 m ranging systematic error were used in the following sections.

3.3. The Influence of Orbit Accuracy of Probes. This section analyses the influence of different Mars probe obit accuracy

TABLE 5: Observing strategies and the accuracy of range measurements.

Strategy	Observing frequency	Stations	Noise level	Systematic errors
Strategy 1	2 hours every day	KS JMS ZP	1m	5m
Strategy 2	2 hours every day	JMS ZP	1m	5m
Strategy 3	2 hours every 5 days	JMS ZP	1m	5m

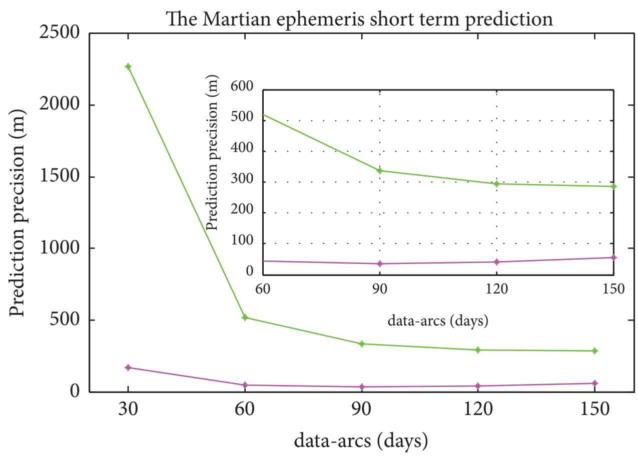

FIGURE 6: The Martian ephemeris short-term prediction with different probe orbit errors.

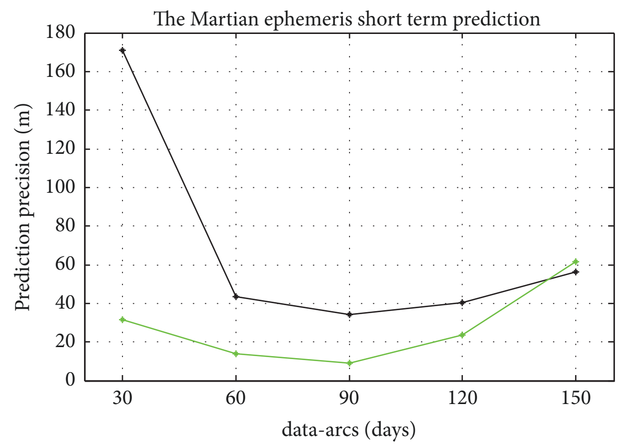

FIGURE 7: The Martian ephemeris short-term prediction with different probe orbit altitudes.

on the short-term predication accuracy of the Mars position. For the (200×200) km Mars probe orbit, with orbital inclination of 0°, considering the probe orbit accuracy of 10 m/ 100 m, respectively, we used 30/60/90/120/150 days' data arc to determine the position of Mars and forecast for 180 days, and the results are shown in Figure 6.

The results showed that the prediction precision of Mars position increased with the increasing of the Mars probe orbit accuracy. The Mars position prediction error using 90/120/150 days' data-arc length was about 300 m for 100 m orbit error, while the precision was better than 50 m for 10 m orbit error.

It can be concluded that Mars probe orbit error is an important source error which can affect the short-term prediction of the Mars position. In order to obtain the Mars orbit with position accuracy better than 50 m, the Mars probe orbit precision should be about 10 m.

3.4. The Influence of Orbit Altitude of Probes. For the Mars probe orbit with orbital inclination of 0° and orbit error of 10 m, considering the probe altitude of 200 km/ 5000 km, respectively, we used 30/60/90/120/150 days' data arc to determine the position of Mars and forecast for 180 days, and the results are shown in Figure 7.

The results indicated that the prediction precision of Mars position increased with the increasing of the Mars probe orbit altitude. For (200×200) km orbit, the Mars position prediction error using 90/120/150 days' data-arc length was about 50 m, while the Mars position prediction error was about 20 m for (5000×5000) km orbit.

It can be concluded that the orbit height of the Mars probe is able to effect the precision of the Mars position prediction. This is mainly because the velocity error of the higher of orbiters is smaller and then the error transmitted to the Mars orbit is smaller, resulting in influencing the orbit determination accuracy of the Mars position.

3.5. The Influence of Orbit Inclination of Probes. Chinese Mars orbiter will fly on a large inclination orbit. The influence of orbit inclination was analyzed and the results are shown in Figure 8.

The results showed that different orbital inclinations had no obvious influence on the Mars orbit determination.

3.6. Summary of the Precision of the Martian Ephemeris Short-Term Prediction. The range bias, the orbit error of probes, and the orbit altitude of probes had obvious impacts on 180-day prediction precision. Table 6 shows the position precision of the Martian ephemeris short-term prediction using different strategies.

4. Conclusions

Improving the accuracy of the short-term prediction of the Mars ephemeris is of great value for the engineering and scientific missions of Mars exploration. In this paper, the simulation analysis method is used to analyze the technical

Table 6: Position precision of the Martian ephemeris short term prediction (unit: m).

Range bias	Probes' orbit altitude	Probes' orbit error	Data-arcs (days)						
			30	60	90	120	150	180	210
none	200 km	10 m	170.67	43.58	31.08	27.43	25.13	25.55	34.16
5m	200 km	10 m	170.91	43.45	34.17	40.45	56.40	179.68	277.59
5m	200 km	100 m	2270.27	517.66	336.74	293.59	286.08		
5m	5000 km	10 m	31.40	14.07	9.05	23.70	61.72		

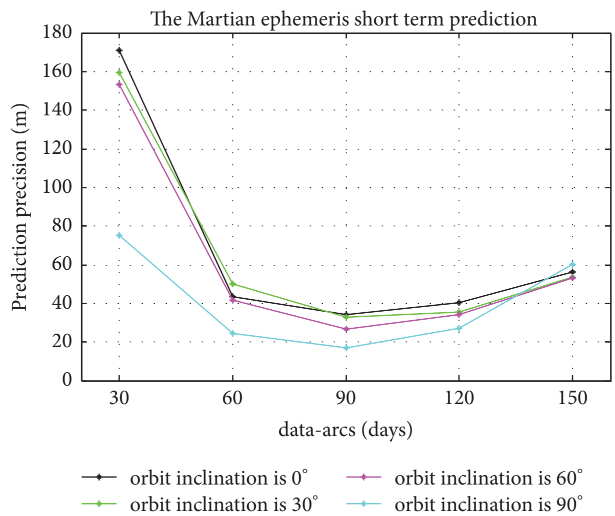

Figure 8: The Martian ephemeris short-term prediction with different probe orbit inclination.

proposal of improving the short-term prediction of the Mars ephemeris and the accuracy that can be achieved by this method. According to the measurement accuracy and the orbit determination accuracy of probes in orbit around Mars, the short-term prediction accuracy of Mars ephemeris was analyzed in the aspects of data arc, observing strategy, range bias, spacecraft's orbit accuracy, spacecraft's orbit altitude, and spacecraft's orbit inclination.

The difference between our work in this paper and the traditional development ephemerides is that instead of producing planetary ephemeris, we put forward a scheme about improving the orbit of a target object in a certain short period according to mission requirements in order that the chances for failure of a probe inserting into Mars orbit and landing can be reduced. The method in this paper is also applicable to the improvement of ephemerides of other planets in the solar system.

Simulation results show that the station distribution and observing frequency have little influence on the Martian ephemeris short-term prediction and the influence of orbit inclination is not distinct. Moreover, range bias affects the prediction accuracy and the arc length for estimation is limited.

The probe orbit accuracy had obvious impacts on the Martian ephemeris short-term prediction. For the (200×200) km orbit, using 90/120/150-day data-arc length, the Mars position prediction error was about 300 m for 100 m Mars probe orbit error, while it was less than 50 m for 10 m Mars probe orbit error.

Orbit altitude of probe could affect the precision of the Martian ephemeris short-term prediction. For the Mars probe orbit error of 10 m, using 90/120/150-day data-arc length, the Mars position prediction error was about 50 m for (200×200) km orbit, while the Mars position prediction error was about 20 m for (5000×5000) km orbit.

Data Availability

The planetary and lunar ephemerides DE421 and DE430 used to support the findings of this study are available at ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii. And simulation data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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