Overview of China's 2020 Mars mission design and navigation

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ABSTRACT

Scheduled for an Earth-to-Mars launch opportunity in 2020, the China's Mars probe will arrive on Mars in 2021 with the primary objective of injecting an orbiter and placing a lander and a rover on the surface of the Red Planet. For China's 2020 Mars exploration mission to achieve success, many key technologies must be realized. In this paper, China's 2020 Mars mission and the spacecraft architecture are first introduced. Then, the preliminary launch opportunity, Earth–Mars transfer, Mars capture, and mission orbits are described. Finally, the main navigation schemes are summarized.

KEYWORDS

China's Mars exploration mission
orbiting, landing, and roaming
orbit design
navigation scheme

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1 Introduction

As the planet most similar to the Earth in the solar system, Mars is often the first choice for a planetary exploration mission. Since the 1960s, a total of 44 Mars exploration missions have been implemented, but only half of them were successful [1]. Subject to the planetary motion laws, each favorable opportunity for a transfer from Earth to Mars appears about every 26 months, which means that there are only three favorable opportunities between 2016 and 2020 [2]. Although the Chinese Mars probe was disclosed for the first time in August 2016, preparations for China's Mars exploration program (CMEP) has been ongoing for several years. In March 2007, the director of the China National Space Administration (CNSA) signed a Russian–Chinese interplanetary exploration cooperative agreement with the head of the Russian Federal Space Agency (RFSA). The RFSA agreed to a piggyback mission for China's small Martian orbiter to be carried by Russia's Phobos-Grunt probe, and the former was planned to separate after the latter's injection into Martian orbit [3]. This Chinese Mars probe was named "Yinghuo-1" (YH-1). Unfortunately, in November 2011, the RFSA announced that their Phobos-Grunt probe had failed to enter the Earth–Mars transfer orbit, which led to the unexpected consequence that China's YH-1 orbiter could not be carried into a Martian orbit [3].

To implement the Mars exploration program independently, the CMEP was officially approved by the CNSA in January 2016 [4]. The CMEP is not only the next major space engineering program after the Chinese Manned Space Project (CMSP) and the Chinese Lunar Exploration Project (CLEP), but it is also the first step in exploring extraterrestrial planets in Chinese history. Its first mission is to realize Mars orbiting, landing, and roaming [4]. In fact, the CMSP and CLEP have developed a useful technical foundation and experience to support the Mars exploration mission [5]. The conceptual phase of CMEP started in September 2014, before receiving approval from CMEP. Twenty months after receiving approval, the conceptual phase switched into the prototype phase [6].

The aim of this paper is to briefly summarize mission design of the CMEP to be implemented in 2020, and the main contents include Mars probe system architecture, launch opportunities, mission orbits, and navigation schemes. The rest of this paper is organized as follows.

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Section 2 reveals the general ideas of China's first Mars mission. Section 3 presents the preliminary results of launch opportunities and mission orbits. Corresponding navigation schemes for each flight phase are described in Section 4. Finally, Section 5 contains conclusions.

2 China's 2020 Mars exploration program

CMEP has been planned as two main steps in the next two decades [4]. The first step contains orbiting, landing, and roaming. The second step is to realize Mars sample return. As the first step mission, China's 2020 Mars mission is introduced as follows based on some published reports about its preliminary conceptual design.

2.1 Mission overview

China's 2020 Mars mission is the first-ever attempt to implement this particular mode of Mars exploration [4]. China's 2020 Mars mission is depicted schematically in Fig. 1, and its basic objectives (scientific and technological objectives) can be summarized as follows.

Scientific objectives [3, 4]: (1) Comprehensive investigation of the Martian space magnetosphere and ionosphere; (2) precise exploration of the Martian gravity field and atmosphere; (3) mapping of Martian surface topography and efficient observation of sandstorms; and (4) survey of rock composition, soil characteristics, and distribution of water ice and minerals on the surface of Mars.

Technological objectives [3, 4]: (1) Advancing Mars probe system technologies, including those used in interplanetary cruising, orbiting Mars, atmospheric entry, parachute descent, safe landing, and surface operation; (2) confirming the orbit design for Mars exploration, from launch and interplanetary cruising to orbiting and landing on Mars, and both realizing and verifying the Earth-to-Mars direct transfer injection; (3) realizing the precision orbit determination for the Mars probe and data transmission from a Mars orbit through a cooperative spacecraft and deep-space network system; and (4) verifying the Mars orbit and surface teleoperation technologies.

Currently, the candidate landing area of China's 2020 Mars mission has been only roughly determined to be in the northern hemisphere and low-latitude areas of Mars. However, the final landing site has not been selected [4]. Due to the use of a solar-powered rover, from the perspective of illumination, the most suitable landing area should be close to the equator of Mars. In addition, more than 99% of the kinetic energy is dissipated by atmospheric deceleration during a Mars landing mission, so a lower-elevation landing site would enable a longer deceleration time and result in a securer landing velocity [1, 5]. The majority of the elevation of the northern hemisphere of Mars is lower than that of the southern hemisphere, and the terrain near the equator is complex. Considering the terrain complexity, elevation, light

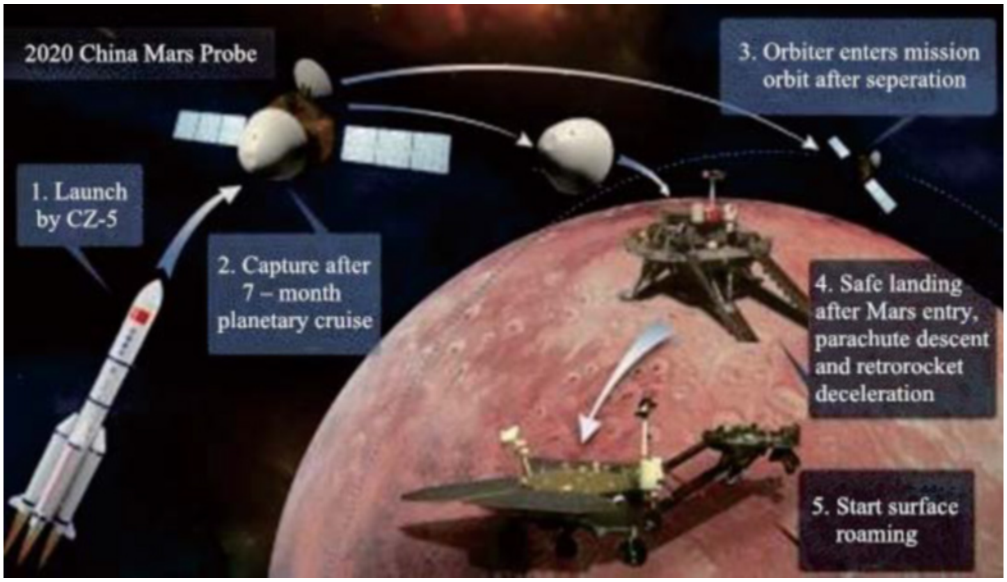

Fig. 1 Schematic diagram of China's 2020 Mars exploration mission [2].

condition, wind speed, visibility requirements during the landing process, and scientific value, more suitable landing areas have been preliminarily determined as zones with latitudes between ∼5° N and ∼39° N [4], as shown in Fig. 2.

2.2 Mars probe architecture

On 23 August 2016, the CNSA announced the appearance and function of China's first Mars probe (see Fig. 3) and solicited international suggestions for a name and logo for the Chinese Mars exploration project [4]. The Mars probe system contains an orbiter and an entry capsule that includes a lander and a rover.

(1) *Orbiter*

The main body of the orbiter is a hexagonal prism structure. A pair of solar arrays that generate electrical energy are arranged symmetrically on two sides of the main body. A high-gain directional antenna and several radio beacon antennas are equipped to communicate with the Earth station. A main engine is installed at the bottom of the orbiter to support orbital maneuvers. Other platform equipment and scientific payloads have not been disclosed.

The main functions of the orbiter include the following [4]: (1) Complete the Earth–Mars transfer and brake at the Mars periapsis position with the lander and rover onboard; (2) implement scientific circum-Mars exploration after releasing the lander and rover in the Mars orbit; and (3) provide a data relay for the Mars lander and rover.

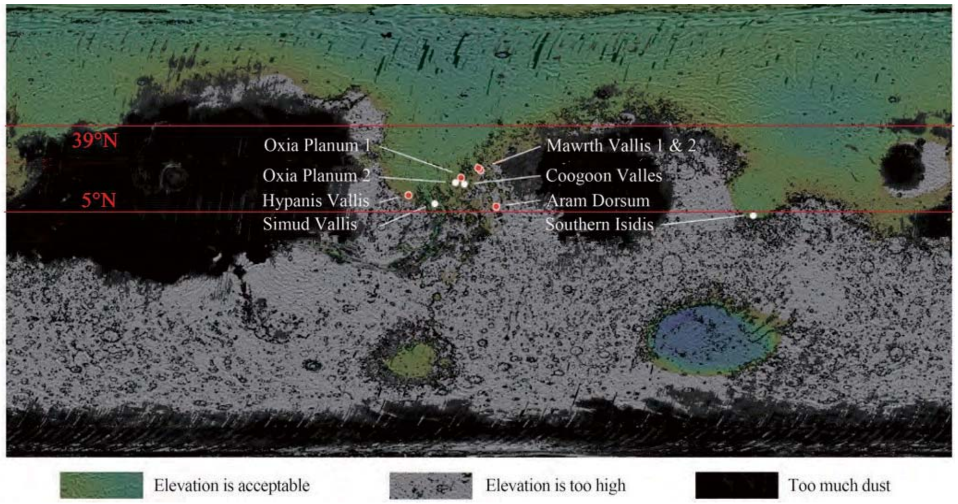

Fig. 2 Candidate landing areas of Chinese first Mars mission. Reproduced with permission from Ref. [7], © *Journal of Deep Space Exploration* 2016.

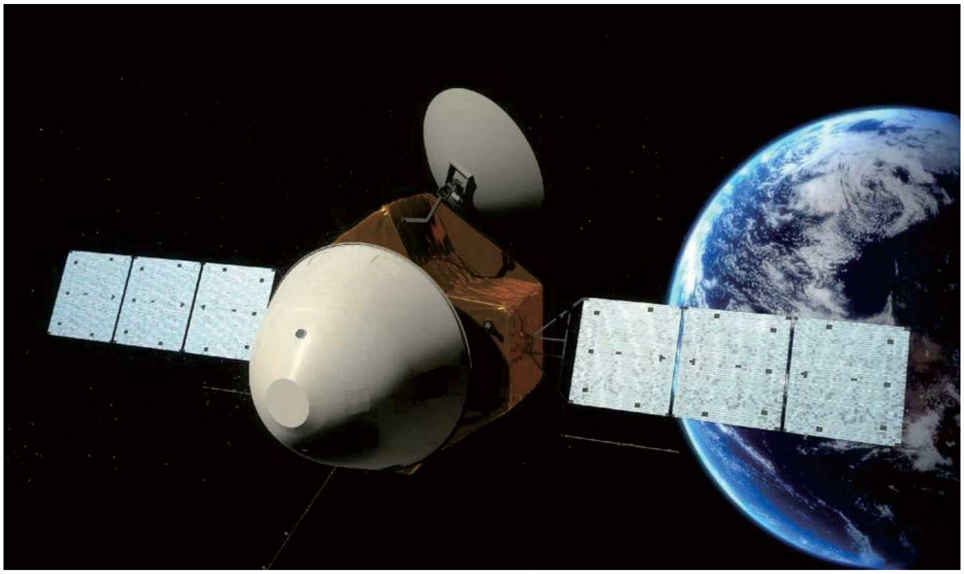

Fig. 3 Conceptual diagram of China Mars probe. Reproduced with permission from Ref. [4], © *Space International* 2016.

(2) *Entry capsule*

China's first Mars entry capsule is designed to carry both the lander and rover to allow them to pass through the Mars atmosphere [4, 8]. The entry capsule consists of a heating shield, a back fairing, a parachute module, and related sensors and apparatus. Similar to previously successful Mars entry vehicles, the shape of the heating shield on the bottom of the entry capsule is a 70° spherical cone. The rear fairing is a double-truncated cone, which resembles the reentry capsule of China's Shenzhou manned spacecraft.

Similar to the Earth reentry process, the entry capsule is required primarily for aerodynamic deceleration. It will protect the lander and rover from the severe aerodynamic heating during the entry phase. Then, a supersonic disk-gap-band parachute will be released from the parachute module at the top of the rear fairing. Next, the heating shield will be discarded after parachute has descended for a set time. Finally, the lander–rover combination will be separated from the rear fairing.

(3) *Lander*

The configuration of the Mars lander is similar to China's lunar lander, Chang'e-3 [8]. As shown in Fig. 4, the lander includes a circular platform, a main variable thrust engine, an omnidirectional antenna, four landing buffering legs, a rover transfer mechanism, several scientific payloads, and other necessary equipment [4].

The variable thrust engine (retrorocket) will be ignited after the lander–rover combination separates from the rear fairing of the entry capsule. It will safely land on the surface of Mars using a powered descent, hazard detection and avoidance, and a final slow vertical descent.

The main functions of the lander include the following [4,8]: (1) To realize safe landing on the Martian surface; (2) to implement *in situ* scientific exploration; and (3) to carry and release a Mars rover for surface roaming exploration.

(4) *Rover*

Similar to the configuration of China's first lunar rover, Yutu [8], China's first Mars rover is designed as shown in Fig. 5. The total mass of the rover is approximately 200 kg [4]. According to the objectives of China's Mars exploration mission, the rover not only has traditional platform subsystems (e.g., communication, thermal control, navigation, motion systems) but is also equipped with a number of scientific payloads, such as a high-resolution camera, radiometer, spectrum analyzer, automatic arm camera, shallow ground radar, and weather module. To adapt to the harsh environment of Mars, multiple composites are utilized to manufacture the rover, such as manufacturing composite memory fiber, aluminum-based silicon carbide, and honeycomb sandwich plat [4]. An independent sleep and wake up mode will be arranged to avoid the dust storms on Mars. In addition, since Mars is farther from the Sun than the Earth, four high-efficiency solar arrays have been designed for the rover to ensure its energy supply. The rover mainly relies on the orbiter for data relay to the Earth, and high-level autonomous control capacity is essential.

China's 2020 Mars probe is planned to be launched by the CZ-5 launch vehicle from the Hainan Wenchang Spacecraft Launch Center in the latter half of 2020 [4]. The probe will be directly sent to the Earth–Mars

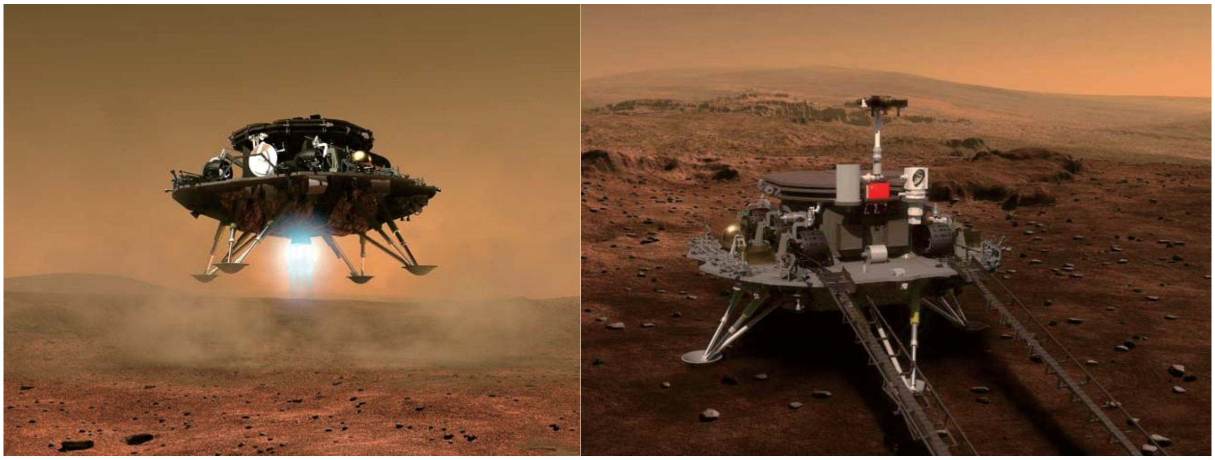

Fig. 4 Conceptual diagram of China's Mars lander. Reproduced with permission from Ref. [4], © *Space International* 2016.

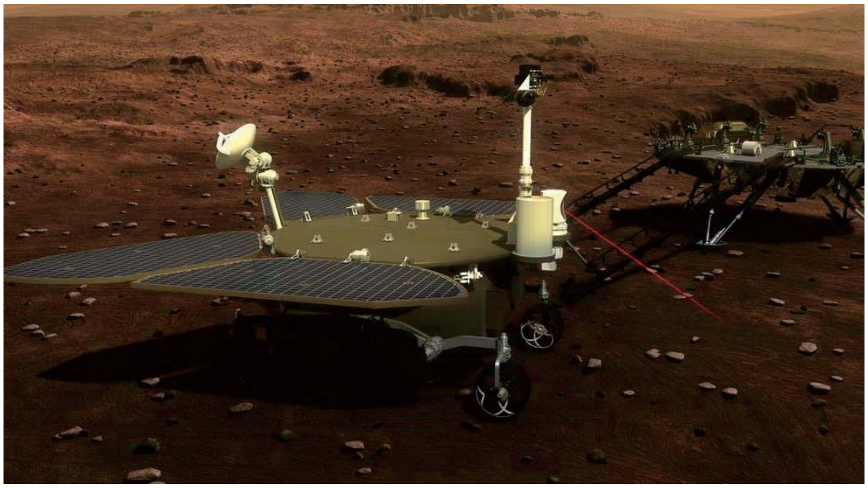

Fig. 5 Conceptual diagram of China's Mars rover. Reproduced with permission from Ref. [4], © *Space International* 2016.

transfer orbit. The probe will be captured by Mars after a 7- or 8-month interplanetary cruise and is scheduled to arrive in a Mars orbit before 1 July 2021. The entry capsule will be separated from the orbiter after orbiting Mars for certain time and will then enter the Mars atmosphere and safely touch down on the surface. After landing, the Mars rover will extend its solar panels, establish direction control of the Earth-point antenna, and report its initial status. Subsequently, the rover will bear off the lander platform and start its roaming exploration on the surface of Mars, and the lander will begin *in situ* exploration. Then, the orbiter will maneuver to its mission orbit for Mars global remote sensing and will provide relay communication services for the entry capsule, lander, and rover. Due to the long transmission delay, a high-level autonomous control capacity of the rover is essential. The orbiter and rover are planned to work for at least 1 Martian year (i.e., 2 Earth years) and 3 months (i.e., ∼92 Earth days), respectively [4, 8].

Compared with past Mars exploration missions, China's 2020 Mars mission has the following remarkable characteristics [8]: (1) The Mars probe consists of an orbiter and an entry capsule, and the entry capsule contains a lander and a rover; (2) the orbiter implements a global exploration mission, and the lander and rover realize a pinpoint landing and local surface exploration mission, respectively; and (3) the orbiter, lander, and rover will support each other through radio communication throughout their mission-cycle. Such an orbiting/landing collaborative mission is desired to obtain more scientific benefits, gather more engineering data, and accumulate more technical foundations for China's subsequent Mars exploration activities.

3 Flight profiles

The flight profiles of China's 2020 Mars mission can be divided into four phases: Earth–Mars transfer; Mars capture; Mars parking; and entry, descent, and landing (EDL). The flight profiles are described preliminarily as follows.

China's 2020 Mars mission will adopt a direct transfer orbit injection, so it is important to determine an optimal launch opportunity [4]. The Earth–Mars transfer phase will take approximately 7 months. The probe will complete a series of trajectory correction maneuvers (TCMs) as well as navigation verification and calibration. The optimal launch opportunity in 2020 is preliminarily obtained by searching for the minimum departure energy (i.e., $C_{3\mathrm{d}}$) in the pork-chop diagram, as shown in Fig. 6. The detailed calculation approach is described in Ref. [9].

Here, the launch opportunity is selected according to the following two conditions: (1) The departure energy is near the minimal value within a limited allowable scope (i.e., the permitted departure energy change of the CZ-5 launch vehicle is $\Delta C_{3\mathrm{d}} < 0.5$ for a direct Earth–Mars transfer injection); and (2) its arrival date is close to the desired date (i.e., 1 July 2021). From Fig. 6, the optimal and suboptimal energy launch opportunities appear in July and August 2020, respectively. Then, it can be found that the minimum energy launch window will open from 10 July to 29 July, for approximately

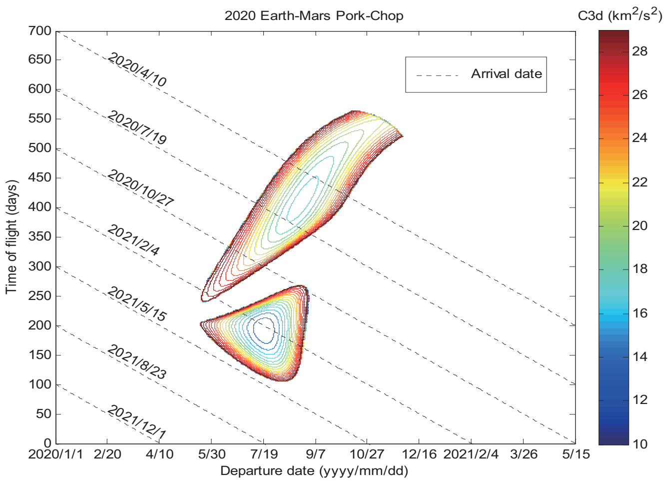

Fig. 6 Launch opportunities schematic: pork-chop diagram.

19 days, and the optimal opportunity is 19 July. As a backup, the suboptimal opportunity opens from 19 August to 2 September, for approximately 14 days. The detailed launch and arrival information for these two cases is listed in Tables 1 and 2, respectively.

To ensure the accuracy of the Mars capture injection, TCMs are always required during the transfer phase to correct trajectory errors caused by various gravitational perturbations or system sensing and execution errors [10]. Additionally, in practice, the TCMs schedule should be properly updated to achieve the capture with the optimal angle of incidence and minimal fuel consumption. Taking the optimal launch opportunity as an example, to enable the Mars probe to be accurately captured in the desired large elliptic orbit around Mars before February 2021, four TCMs have been preliminarily designed based on the calculation results using the genetic algorithm and B-plane parameters [10–12]. Details of the TCMs are listed in Table 3.

As shown in Fig. 7, the first TCM is scheduled on the 9th day after launch. Its main goal is to eliminate the launch injection error. Therefore, the cost of the TCM can be significantly reduced by improving the injection accuracy of the launch. The second TCM is designed to occur on the 65th day after launch and aims primarily to correct the execution error of the propulsion system. The first two TCMs basically ensure that the probe can be captured by Mars. The other two TCMs are scheduled to occur at 10 days and 6 hours before the capture, respectively, and are primarily aimed to successively improve the injection accuracy so the spacecraft can be delivered to the desired Mars capture orbit.

After braking at periareon, the spacecraft will enter

Table 1 Energy-optimal launch opportunity

Flight parameter	Launch period open	Optimal launch opportunity	Launch period close
Departure date (yyyy/mm/dd)	2020/07/10	2020/07/19	2020/07/29
Arrival date (yyyy/mm/dd)	2021/01/21	2021/01/28	2021/02/06
Time-of-flight (day)	195	193	202
C_{3d} (km^2/s^2)	13.7658	13.1826	14.0653
Arrival V-infinity (km/s)	2.9894	2.8528	2.6958

Table 2 Energy-suboptimal launch opportunity

Flight parameter	Launch period open	Suboptimal launch opportunity	Launch period close
Departure date (yyyy/mm/dd)	2020/08/19	2020/08/25	2020/09/02
Arrival date (yyyy/mm/dd)	2021/09/21	2021/10/10	2021/11/05
Time-of-flight (day)	398	411	429
C_{3d} (km^2/s^2)	16.5743	16.5074	16.6680
Arrival V-infinity (km/s)	3.6503	3.8058	4.0498

Table 3 Preliminary design results of TCMs

Date of TCM	TCM (m/s)	Residual error $\delta\lvert B\rvert$ (km)	Execution error 3σ
2020/07/28	37.625	33530	5%
2020/09/22	0.709	1452.3	5%
2021/01/18	0.033	293.08	5%
2021/01/28	0.017	7.3245	5%

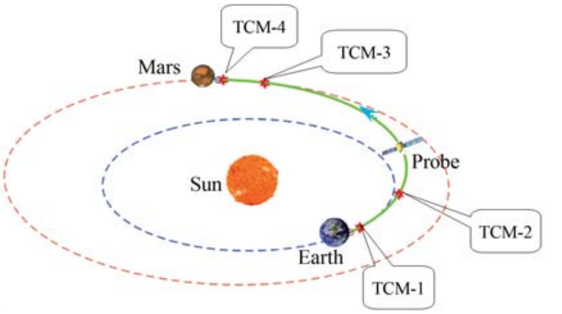

Fig. 7 Schematic diagram of TCMs during the Earth–Mars transfer.

an elliptic capture orbit around Mars with an orbital period of ∼11 days. Then, the spacecraft is scheduled to enter an elliptic parking orbit with an orbit period of ∼2 days. Because the landing area is selected in the low-latitude zone, the periapsis of the parking orbit is designed to be near the equator of Mars, and the entry capsule will separate from the orbiter near the periapsis of the parking orbit. To realize the global remote sensing exploration, the inclination of the orbiter's mission orbit is approximately 90° (i.e., polar orbit) [13], and its orbital period is approximately 8 hours. The polar orbit for remote sensing is realized by changing the orbital plane at apogee of the parking orbit. A schematic diagram of the Mars capture, parking, and mission orbits is depicted in Fig. 8.

After the separation, the entry capsule will enter the Martian atmosphere. The lander–rover combination will safely touch down on the Martian surface through the successive use of hypersonic deceleration, parachute deceleration, retrorocket deceleration and hazard avoidance, and landing legs buffering. The EDL profile of the China's 2020 Mars mission is preliminarily designed as shown in Fig. 9. The rover will be released from the lander and will enable its scientific exploration mission. The initial work of the orbiter is to monitor the state of the entry capsule and lander–rover combination during the Mars EDL. Then, the orbiter will maneuver to the scheduled remote-sensing orbit for global exploration while providing a communication relay between the Earth stations and the rover and lander.

4 Navigation schemes

According to the experiences and technical accumulations in CLEP, deep-space network (DSN) based navigation and autonomous navigation modes will be adopted for different flight phases of China's 2020 Mars mission [14, 15].

4.1 DSN-based navigation

China's 2020 Mars mission will adopt a DSN-based navigation scheme for interplanetary transfer and Mars orbiting, whereas the autonomous optical navigation will be verified simultaneously [16, 17].

The DNS-based navigation scheme, i.e., Very Long Baseline Interferometry (VLBI) combined with the Unified X Band (UXB) measurement, has been used in CLEP. It also has been verified in a Mars Express orbit determination test. The test results show that the accuracy reaches 500 m for position and 0.1 m/s for velocity [14, 16].

China's VLBI observation network, which consists of the existing four observation stations, a data processing center, and three new VLBI stations (i.e., Jiamusi, Kashi, and South America), is shown in Fig. 10. The VLBI network will provide the precise angle and angular rate data of the Mars spacecraft in space [18]. The UXB observation will be used to obtain the range and velocity measurements of the Mars probe in space, as shown in Fig. 11 [16]. Then, the three-dimensional

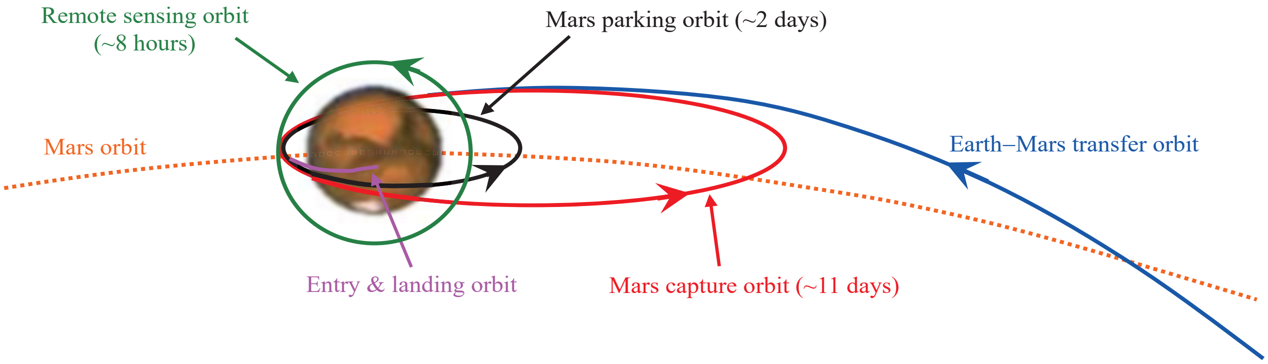

Fig. 8 Schematic diagram of the Mars capture, parking, and mission orbits.

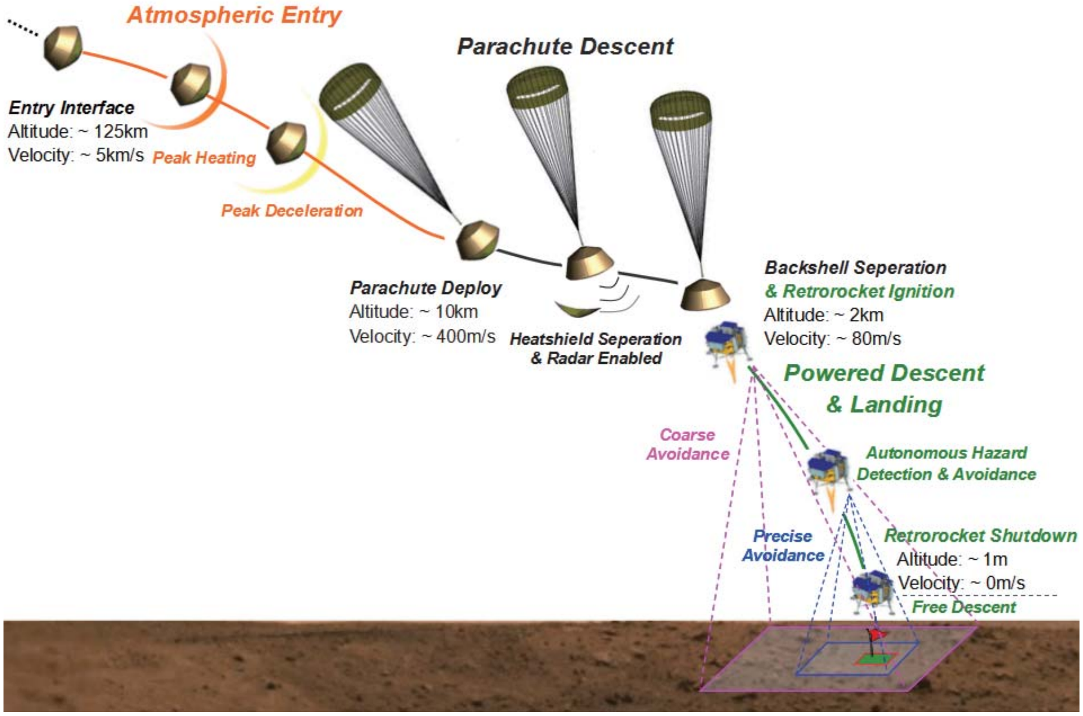

Fig. 9 Preliminary design results of Mars EDL profile.

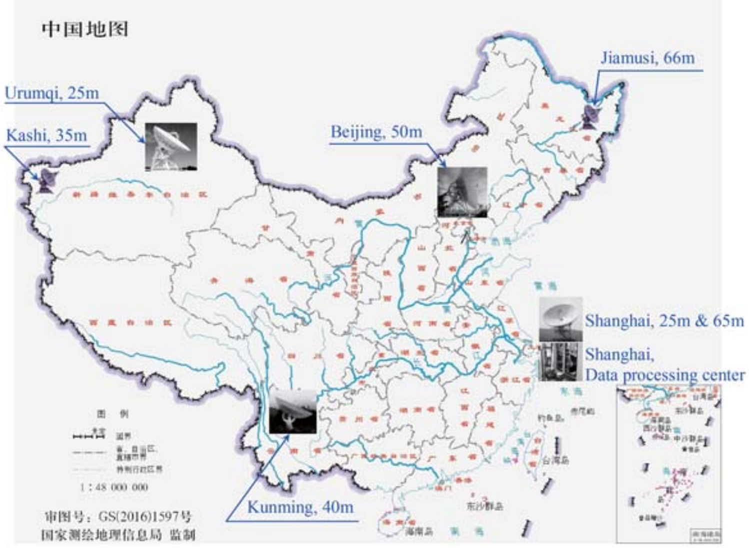

Fig. 10 China's VLBI observation network. Reproduced with permission from Ref. [18], © *Journal of Astronautics* 2010.

position and velocity data of the Mars probe can be estimated accurately through data fusion. Finally, the computed navigation results will be uploaded to update the onboard navigation of the Mars spacecraft.

4.2 Autonomous optical navigation test

Autonomous optical navigation technology for the interplanetary transfer and Mars orbiting is proposed to be a test item in China's 2020 Mars mission [15, 17]. It is expected to replace the DSN-based navigation for a part of the flight phases in future Chinese Mars and asteroid exploration missions. To this end, the accuracy of autonomous optical navigation should be equal to or better than that of the DSN-based navigation.

The optical navigation camera will be used to obtain the gray image of all celestial bodies within its field-of-sight, and the line-of-sight vector and apparent radius of special celestial bodies (e.g., Mars, Martian natural satellites, asteroids, Earth, Moon, constellation) will be extracted (see Fig. 12) [15, 19]. According to the

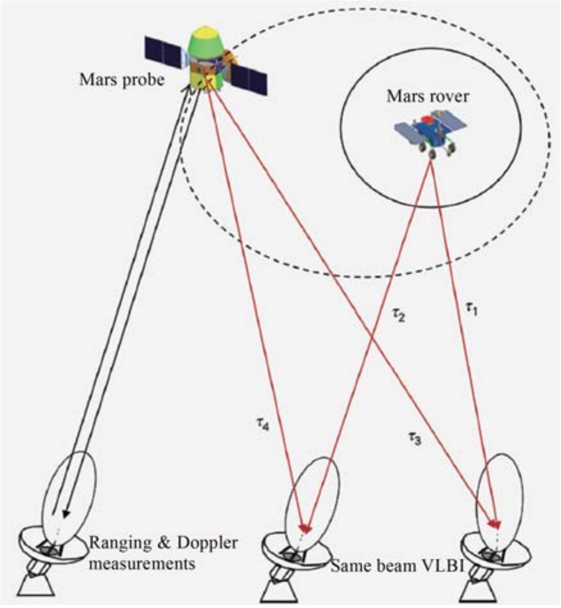

Fig. 11 Schematic diagram of the UXB and VLBI observation. Reproduced with permission from Ref. [16], © *Scientia Sinica Physica Mechanica & Astronomica* 2015.

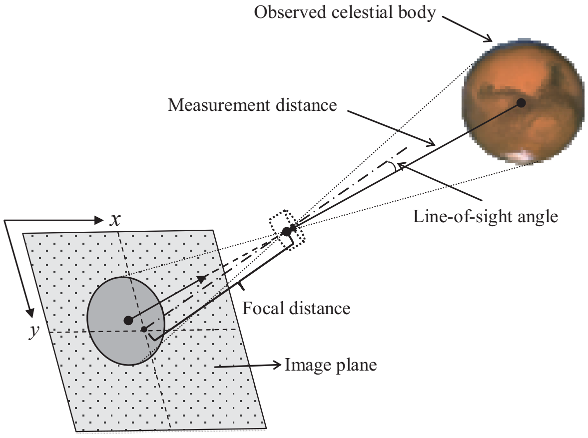

Fig. 12 Schematic diagram of optical navigation.

extracted line-of-sight vector and apparent radius, focal distance, and onboard ephemeris or star map, the navigation data of the spacecraft (i.e., position and orientation) can be estimated onboard.

As shown in Fig. 13, for China's 2020 Mars mission, the spacecraft is scheduled to be in the Sun pointing mode during interplanetary transfer. The Earth–Moon system, star/constellation, and Mars system can be successively observed by the optical navigation camera [15, 17, 19]. To calibrate the onboard optical navigation parameters, the Earth and Moon will be observed by the optical navigation camera at the initial stage of the interplanetary transfer. During the middle stage of the interplanetary transfer, the image sizes of both the Earth–Moon and Mars systems will be too small to identify, so the optical navigation camera will be used as a star sensor [20] and only orientation information will be estimated according to the optical image and onboard star map. The Mars system will be continuously observed during the last 10 million kilometers to Mars, and both the relative and absolute navigation data of the spacecraft can be estimated according to the image sizes of Mars and the ephemeris [21].

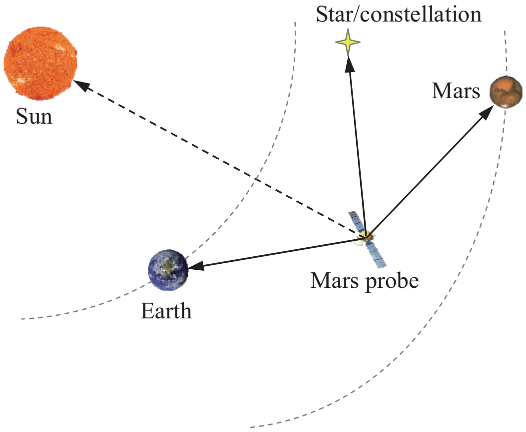

Fig. 13 Sketch of measurement geometry of optical navigation.

4.3 EDL navigation

Before the entry capsule separates from the orbiter, the navigation data of the entire spacecraft (i.e., entry capsule–orbiter combination) will be accurately updated and confirmed by DNS [5]. Then, the initial navigation parameters of the entry capsule will be given by the onboard navigation system of the orbiter. The Mars entry navigation for China's 2020 Mars mission is scheduled to adopt an inertial navigation mode (dead reckoning). It will be the only navigation mode for the entry capsule from the capsule–orbiter separation to the capsule–heating shield separation. Meanwhile, the range and velocity measurements via the ultra-high frequency band radio communication between the orbiter and entry capsule will be tested and verified [22]. Additionally, a flush air data sensing system will be employed to sense the aerodynamic data during the hypersonic entry process [23]. The latter two measurement approaches are only used to gather more first-hand flight data, which is conductive for analyzing, assessing, and improving the initial design.

The reentry navigation scheme used by the Shenzhou manned spacecraft and the descent and landing navigation scheme used by the Chang'e-3 lunar lander will be inherited and improved for the descent and landing process of China's 2020 Mars mission [8, 24]. Until heat shield separation occurs, the navigation errors will have accumulated, but a higher navigation accuracy is usually required for descent and safe landing. During the parachute descent, a laser range finder and a microwave ranging velocity sensor will be introduced to correct the inertial navigation results and obtain more accurate relative navigation data, and during the powered descent and landing phase, an optical imaging sensor and laser three-dimensional imaging senor will be introduced to obtain terrain data for hazard detection and to estimate the horizontal velocity and position to further enhance the integrated navigation, based on an IMU/laser range finder/microwave ranging velocity sensor. During the surface operation process, inertial dead reckoning and binocular visual navigation will be employed for the Mars rover. The initial coordinates of both lander and rover will be accurately measured and determined by using DNS [25, 26].

5 Conclusions

China's 2020 Mars exploration project has been started. This paper has described a brief summary of China's 2020 Mars mission plan and the spacecraft's preliminary design, including the scientific and engineering objectives, orbiter, entry capsule lander, and rover. According to the mission plan, the preliminary orbit designs and navigation schemes were also presented. With advances in the design and development work, more detailed and accurate results will be worked out and will be reported in future articles.

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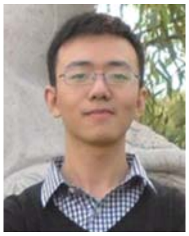

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