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Design of communication relay mission for supporting lunar-farside soft landing

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Abstract Chang'E-IV will be the first soft-landing and rover mission on the lunar farside. The relay satellite, which is located near the Earth-Moon L2 point for relay communication, is the key to the landing mission. Based on an analysis of the characteristics of the task and the technical difficulties associated with the relay satellite system, the overall design scheme of the relay communication mission is proposed in terms of trajectory design and communication system design among other aspects. First, according to the complex dynamic environment, a mission orbit that serves as an uninterrupted communication link is presented. A short-duration and low-energy transfer trajectory with lunar flyby is discussed. Orbital correction and a low-cost control strategy for orbit maintenance in the Earth-Moon L2 point region are provided. Second, considering the existing technical constraints, the requirement of relay communication in different stages and the design schemes of frequency division and redundant relay communication system are introduced. Finally, based on the trajectory design index and the performance of the communication system, the overall design scheme of the relay communication mission is proposed. This mission will provide the technical support and reference required for the Chang'E-IV mission.

Keywords lunar farside, soft landing, relay communication, Earth-Moon Lagrange point

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1 Introduction

Chang'E-IV will be the first attempt in the world at soft-landing and rover mission on the lunar farside. Owing to synchronous rotation of the moon, ground stations cannot directly communicate with the lander and rover on the lunar farside. Therefore, a relay satellite is indispensable for transmitting the scientific data obtained by the lander and rover back to the earth and to provide the corresponding measurement and control support. In addition, the relay satellite will be equipped with instruments to carry out scientific exploration and technical verification from its unique spatial location.

Lagrange points represent the general term of five dynamic libration points in a circular restricted three-body problem, including three collinear libration points (L1, L2 and L3) and two triangular libration points (L4 and L5). The distribution of libration points in the Earth-Moon rotating frame is shown in Figure 1.

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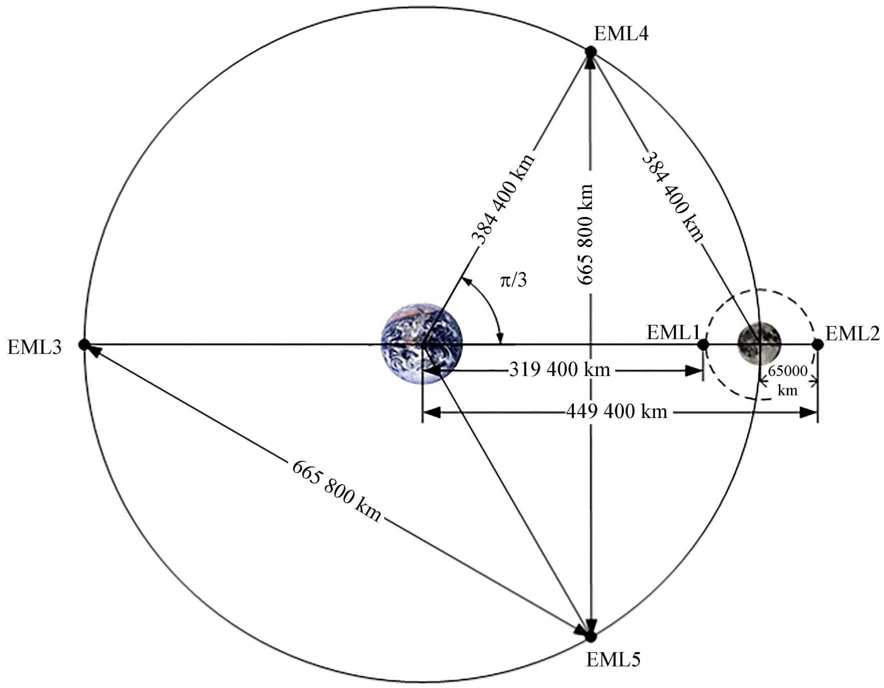

Figure 1 (Color online) Geometric relationships of the Earth-Moon system, and distributions of libration points.

Libration points have been investigated widely in space exploration and space science observation. Farquhar pointed out that a space station on a periodic orbit around the Earth-Moon libration points has advantages in lunar exploration over one in a circumlunar orbit [1,2]. Burns et al. [3] investigated the concept of human deep space exploration based on the lunar L2 point. Radio-astronomy measurements conducted by taking advantage of libration points are proposed in the Cosmic Vision program [4]. Owing to the unique value of libration points, as well as the requirements and constraints of the Chang'E-IV relay task, the region near L2 in the Earth-Moon system is selected as the mission area of the relay satellite. Relay communications services, telemetry and telecontrol supports, and the explorations of relevant space science will carried out here.

2 Analysis of characteristics and requirements of relay task

2.1 Characteristics of relay task

According to the task requirments, the relay satellite needs to use its own propulsion system to realize the transfer from Earth to the Earth-Moon L2 point and for long-term orbital maintenance. On the one hand, the relay satellite must realize forward and backward communication with the lander and rover of Chang'E-IV on the lunar farside. On the other hand, the relay satellite must provide real-time or time-delay relay communication with the uplink and the downlink of the Earth telemetry, track and command (TT & C) system, as well as the ground application system. The relevant links are shown in Figure 2.

The main features of the relay satellite task can be summarized as follows:

(1) Relay communication as main task. The relay satellite provides real-time/quasi-real-time communication support to the lander and rover of Chang'E-IV during the entire course of circumlunar, powered descent and in the surface working stages to ensure smooth implementation of the task.

(2) Special mission orbit. The relay satellite will run for a long time in the halo orbit, where the dynamic environment of space is rather complex.

(3) Long-term scientific exploration. The relay satellite will not only complete the relay communication task, but also carry out long-term scientific exploration and technical test validation.

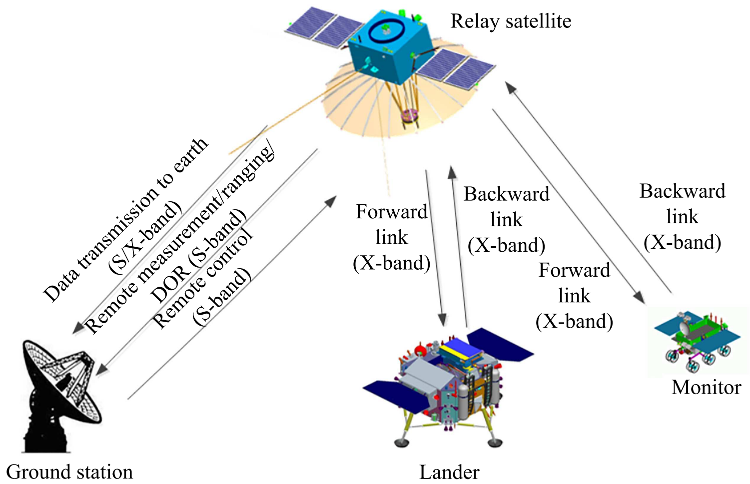

Figure 2 (Color online) Measurement and control of relay satellite and relay communication link.

(4) High reliability requirments. The relay satellite will guarantee relay communication for the lander and the rover. High reliability is required for both relay communication load and platform sub-systems.

2.2 Demands and challenges of relay task

The following challenges will be encountered in the implementation of the relay task:

(1) Various constraints on mission orbit design. These constraints contain coverage rate for landing area, minimum elevation angle of lander/rover antennas, minimum Probe-Earth-Moon angle, maximum Earth-Probe-Landing point angle, maximum distance between satellite and landing point, and maximum duration of shadow occlusion. These constrains are non-uniform, which makes the task of designing the mission orbit difficult.

(2) Difficulties in designing transfer orbit. The relay satellite must carry all fuels itself after separation from the carrier. Hence, low energy transfer must be considered as a primary factor in trajectory design. In addition, the transfer time should be shortened considering the constraints imposed by task time. However, low energy and short transfer time are non-uniform constraints on orbit design. Therefore, a compromise is achieved between these two factors.

(3) Difficult to maintain mission orbit for extended duration. During the mission, the relay satellite will be effected by gravitation from multi-body systems, including the Sun, Earth, Moon, and other planets. Moreover, it will be effected by non-spherical perturbation of Earth/Moon and solar radiation pressure. It is challenging to maintain the satellite in orbit over the long term with low energy consumption in such a complex dynamic environment.

Solving the above problems is imperative to the success of Chang'E-IV's relay satellite task. In addition, the task has high requirements in terms of lifespan and reliability, weight limit of the satellite, short development period. Therefore, it is important to comprehensive analyze the characteristics of Chang'E-IV's relay satellite task and to determine a reasonable and feasible solution.

3 Orbit design and analysis of relay satellite

The design of the relay satellite's orbit is an important part of the overall task design, which includes mission orbit design, transfer trajectory design, error correction, and mission orbit maintenance.

3.1 Mission orbit design

Although the circumlunar orbit, which is close to the lunar surface and easy to achieve, can be used for lunar relay communication, according to the dynamics features of the orbit, it is not possible for a

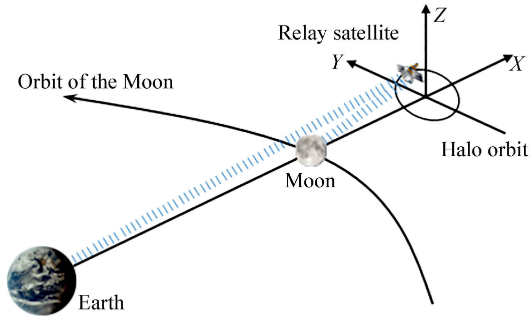

Figure 3 (Color online) Relay satellite located in Earth-Moon L2 halo orbit, and communications for lunar farside.

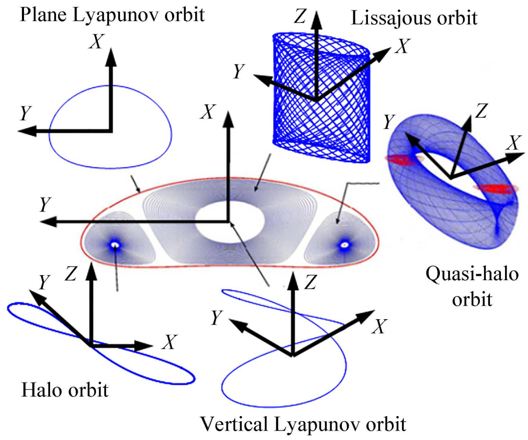

Figure 4 (Color online) Orbital types near the libration point.

single satellite to fulfill continuous communication in invisible areas such as the lunar farside. Using a constellation of multiple satellites will lead to complex monitoring and control efforts, increasing cost, and greater risk. Based on the characteristics of lunar synchronous rotation, if the relay satellite is deployed in the periodic orbit near the L2 point in the Earth-Moon system, a single satellite can establish a continuous communication relay with the lander and the rover on the lunar farside (as shown in Figure 3) by taking advantage of the unique dynamics property of this point. Farquhar studied this problem in depth [5–7]. Although the visibility of the relay satellite to one ground station is limited, usually less than 8 h, there are several ground stations on the Earth, including two ground stations in South America. In that case, the satellite can establish a continuous communication relay with ground stations for more than 23 h each day.

Compared with the circumlunar orbit, the periodic orbit around the Earth-Moon L2 point has the following advantages:

(1) The periodic orbit is visible uninterruptedly to the lunar farside for a long time and has a high coverage rate for the lander and the rover.

(2) The periodic orbit can maintain high visibility with the Earth, which is convenient for relay communications and for tracking and control from the ground station.

(3) The periodic orbit is slightly blocked by the Earth or the Moon and is well illuminated [8], which is beneficial from the overall satellite design viewpoint.

According to the theories on CRTBP, there are many types of periodic and quasi-periodic orbits near the equilibrium points (L1, L2, and L3), such as Lyapunov orbits, halo orbits, Lissajous orbits, and quasi-halo orbits, as shown in Figure 4.

The Lyapunov orbits consist of two types of orbits: planar and vertical. Planar Lyapunov orbits always move in the XY plane, while the vertical ones move mainly in the Z direction and pass through the X axis. Lissajous orbits are non-closed orbits, of which the amplitudes in the X direction and

Table 1 Comparison and analysis of halo and Lissajous orbits

Index	Halo orbit	Lissajous orbit
Earth communication coverage condition	No Moon occlusion, always visible to the Earth	Short-time disruption due to lunar shadow
Shadow condition	Shadows caused by both the Earth and the Moon	Shadows caused by both the Earth and the Moon
Cost of orbit insertion	Relatively high	Relatively low
Velocity increment of orbit maintenance	Relatively small	Relatively large
Frequency of orbit maintenance	Equivalent frequency	Equivalent frequency
Antenna beam angle for Earth communication	Relatively small	Comparatively large
Angle variation range of Sun relative to satellite Y-axis (shown in Figure 15)	Relatively small	Comparatively large

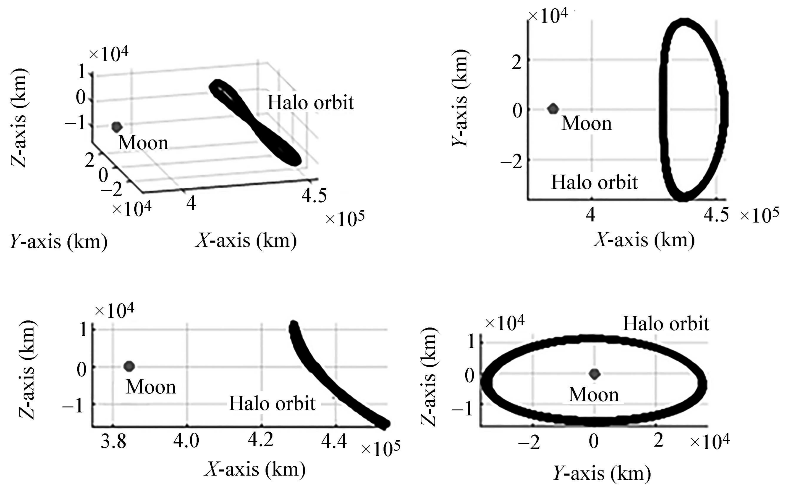

Figure 5 Halo orbit in the region of Earth-Moon L2.

the Y direction are coupled. The amplitude in the Z direction is free. The projection of this orbit in the XY plane is approximately elliptical, and in three-dimensional space, it forms an approximate two-dimensional cylindrical surface. Halo orbits are closed curves in space. Their states satisfy certain relationships. According to the distribution of halo orbits in the XZ plane, they can be divided into the South and the North groups. Quasi-halo orbits are also non-closed orbits, which surround halo orbits and form a two-dimensional torus [9–14].

Both the plane and the vertical types of Lyapunov orbits are affected by long-term lunar shadow, which affects communication between the relay satellite and the ground station. Therefore, halo or Lissajous orbits are more suitable as the mission orbit for the relay satellite. A comparative analysis of these two types of orbits is given in Table 1.

According to Table 1, halo orbits offer better communication conditions and lower cost of orbit maintenance than Lissajous orbits. Moreover, considering the position of the landing site, the south halo orbit is selected as the satellite's mission orbit. The amplitude of this halo orbit is selected to be about 13000 km in the Z direction to balance communication performance and fuel consumption. The mission orbit in the rotating frame is shown in Figure 5.

3.2 Transfer trajectory design

Transfer trajectories from the Earth to the Earth-Moon L2 halo orbit can be classified into three types as follows.

(1) Direct transfer. This involves direct transfer of the relay satellite into the region near the Earth-Moon L2 by applying two impulses [15–17]. One impulse is applied at the perigee and the other is applied

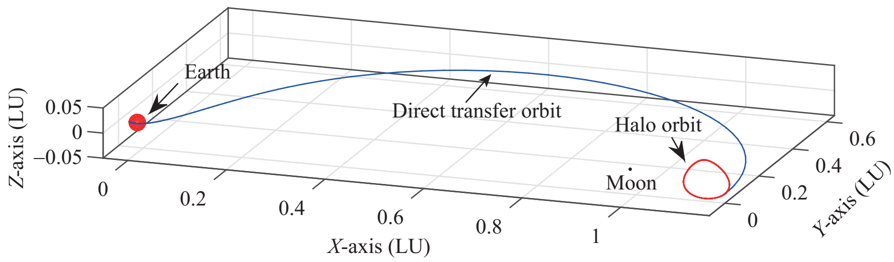

Figure 6 (Color online) Direct transfer trajectory (LU: Earth-Moon distance).

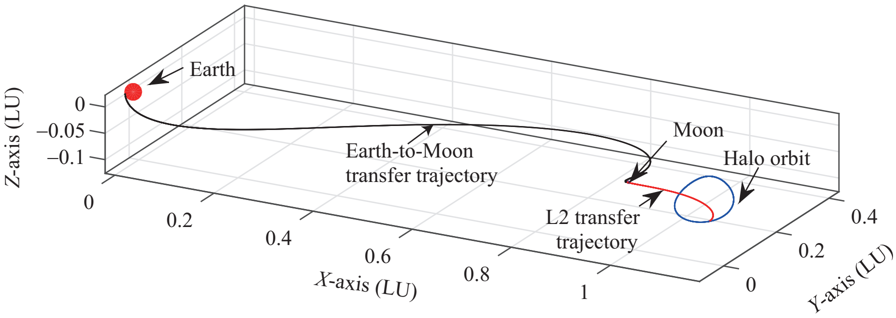

Figure 7 (Color online) Transfer trajectory with lunar flyby.

to send the satellite into the mission orbit. The required velocity increment is about 900–1000 m/s after the satellite separates from the launch vehicle. The flight time is about 6 to 7 days. The transfer path is shown in Figure 6.

(2) Lunar flyby transfer. The relay satellite is first sent to the Earth-Moon transfer trajectory by means of a launch vehicle. An additional maneuver is performed at the perilune to send the satellite into the stable manifold or quasi-manifold of the (quasi-) periodic orbits near the Earth-Moon L2 point. When the satellite reaches the L2 region, one or several small impulses are applied to ensure its entry into the predetermined mission orbit [18,19]. The transfer increment for this type is about 200–300 m/s. The flight time in the translunar trajectory is 4 to 5 days. Additionally, 5–10 days are required to enter the near Earth-Moon L2 region. Generally, it takes 3 to 4 weeks to adjust the orbital phase and insert the relay satellite into the mission orbit. The transfer trajectory is shown in Figure 7.

(3) Low-energy transfer. Low-energy transfers in the Earth-Moon system are of various types, and they can be divided into the following three main groups: (a) Low-energy transfer based on the Sun-Earth L1/L2 point, which means the relay satellite arrives at Sun-Earth libration L1/L2 point first and then returns to the Earth-Moon L2 point [20–22]. This process includes multiple amendments to match the Sun-Earth and the Earth-Moon manifolds. The transfer orbit is shown in Figure 8. (b) Low-energy transfer based on Earth-Moon L1 point [23, 24], which means the relay satellite is transferred to the Earth-Moon L1 point first and is then transferred to the Earth-Moon L2 point by heterclinic connection between points L1 and L2. The transfer orbit is shown in Figure 9. (c) Low-energy transfer in the Earth-Moon space based on the characteristics of the three-body system [25, 26]. The transfer orbit is shown in Figure 10. The speed increment of low energy transfer is about 0–200 m/s. The flight time will be more than 30 days, even 2–3 years.

A comparison of three transfer orbits is given in Table 2. The velocity increment required for direct transfer is large and cannot satisfy the design constraints. For low energy transfer, the required velocity increment is small, but the transfer time is long, which makes it difficult to meet the requirements of the Chang'E-IV project. Lunar flyby transfer has moderate velocity increment and relatively short transfer time. The transfer includes two segments: Earth-Moon transfer and manifold/quasi-manifold transfer. These two segments can be matched by applying a maneuver near the perilune. This transfer can result in savings in terms of the flight time by taking advantage of the direct Earth-Moon transfer. Meanwhile, low-energy orbit insertion can be achieved with the stable manifold's characteristics of periodic orbits

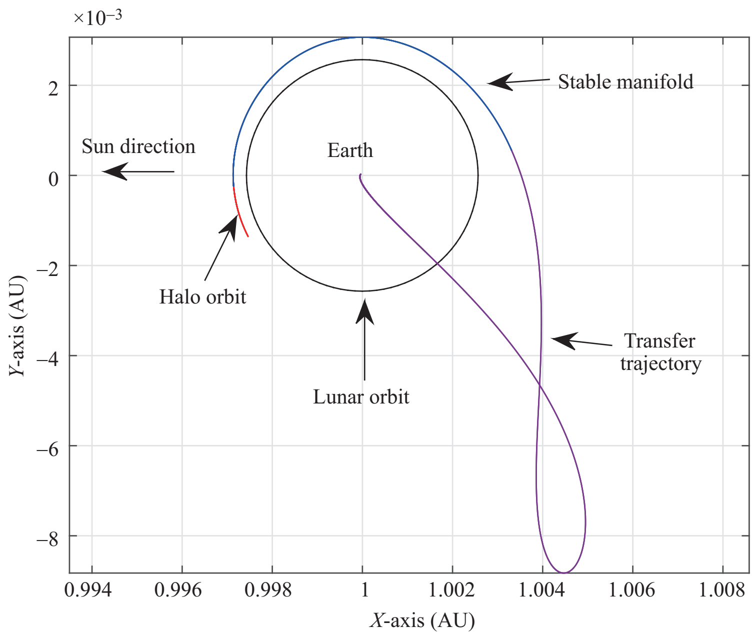

Figure 8 (Color online) Flight trajectory of low-energy transfer via Sun-Earth L2 point (AU: Sun-Earth distance).

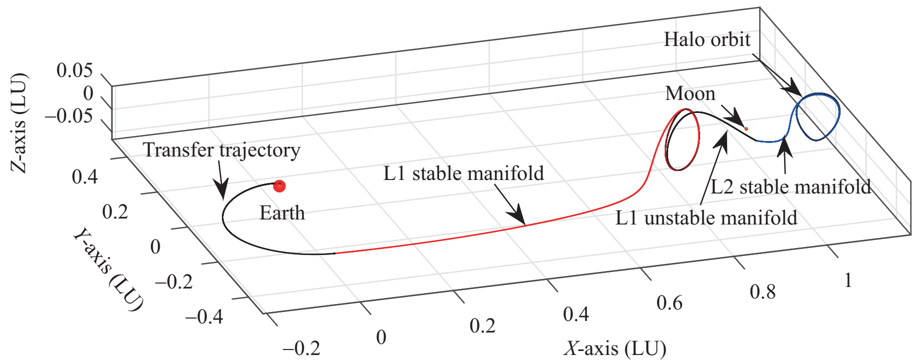

Figure 9 (Color online) Flight trajectory of low-energy transfer via Earth-Moon L1 point.

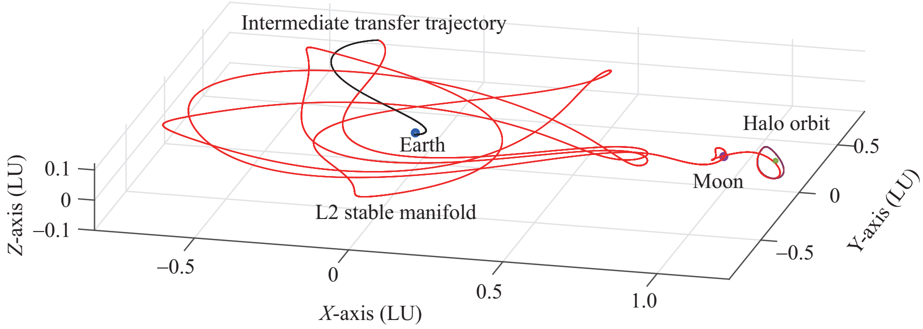

Figure 10 (Color online) Flight trajectory of low-energy transfer in three-body system.

near the equilibrium point, which can reduce fuel consumption during the transfer. It is an appropriate choice for the relay satellite considering the constraints of flight time and fuel consumption.

3.3 Error analysis and midcourse correction

Owing to shortcomings in the launch accuracy, orbit prediction accuracy and control accuracy, the actual transfer trajectory of the relay satellite may deviate from the reference trajectory. Therefore, several

Table 2 Comparisons of three types of transfer trajectories

	Velocity of perigee when launching	The time of flight to the L2 point	Velocity increment	Application
Direct transfer		Short transfer time, about 6–7 days	About 900–1000 m/s	Few application
Lunar flyby transfer	About 10.9 km/s	Relative short transfer time, about 3–4 weeks	About 200–300 m/s	CE-5T in-orbit verification
Low-energy transfer		Long transfer time, from 1 month to 3 years	About 0–200 m/s	Widely applied to exploration mission

Table 3 Deflection of trajectory in rotating frame

Parameters	Mean	Standard deviation	Maximum
Position error in X direction (km)	−2387.330	9161.371	34610.423
Position error in Z direction (km)	1054.920	3725.730	12450.725
Velocity error in X direction (m/s)	−23.539	78.788	335.301
Velocity error in Y direction (m/s)	4.984	23.778	88.371
Velocity error in Z direction (m/s)	4.714	18.489	58.695
Cross-time error (min)	104.347	260.616	962.599

midcourse are required to rectify such deviation and maintain a precise trajectory. Generally, during the Earth-Moon transfer segment, two or three corrections are planned to ensure the trajectory is in its perilune state. Moreover, because of the sensitive dynamic environment near the Earth-Moon L2 point, small errors after perilune may be amplified severely on the L2 transfer trajectory. The error distribution after the perilune maneuver is analyzed. The motion of the relay satellite is integrated using a high-fidelity dynamic model. The initial state of the relay satellite is at the perilune after maneuver. The terminal condition is crossing the XZ-plane in the Earth-Moon rotating frame. The errors in the initial position along the radial direction relative to Earth (R), tangential direction to the trajectory (T), and normal direction relative to the orbital plane (N) are 0.3, 5.7, and 5.6 km (3σ), respectively. The initial velocity errors along these three directions are 0.1, 2.3, and 1.0 m/s (3σ), respectively. For each simulation, we recorded the final states and the transfer times and compared them with the nominal transfer trajectory. In total, 100 Monte-Carlo simulations were performed. Table 3 shows the statistical results of the deflection of trajectory. The errors are so large that the satellite might fail to get into the mission orbit. Therefore, three more corrections were planned to improve the injection accuracy and lower the total cost. The entire flight sequence of the lunar flyby transfer is shown in Figure 11. Based on the correction process, the simulation shows that the total increment of transfer trajectory is about 310 m/s, in which the velocity increment is about 20 m/s for lunar transfer trajectory correction and about 25 m/s for lunar-L2 trajectory correction.

3.4 Maintenance of mission orbit

The halo orbit about the Earth-Moon L2 point is unstable and is sensitive to the perturbation caused by the sun's gravitation, solar radiation pressure, and orbital eccentricity of the Moon. In that case, the satellite cannot run in the nominal orbit for a long time. Orbit maintenance must be implemented on a regular basis. In addition, the uncertainty of orbital determination is an important reason for orbit maintenance.

There are many maintenance strategies for periodic or quasi-periodic orbits near the equilibrium point including the targeting method [27–29], optimal continuation strategy [30], Floque theory method [31], H-∞ control [32] and $\theta - D$ control [33]. The stationkeep of satellite based on solar radiation pressure and tether is investigated as well [34]. However, a few of the maintenance strategies need sophisticated calculation, which is difficult to achieve in practical missions. Here, a multi-cycle predictive correction strategy is adopted. This strategy integrates the orbit in units of 1/2 period to ensure that when crossing the XZ plane, the velocity in the X-axis direction is 0 m/s. The previous correction value is used as the

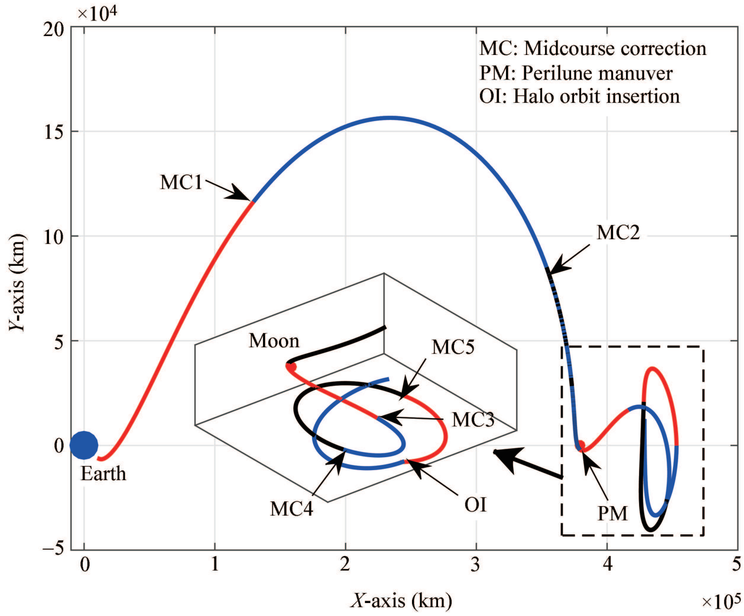

Figure 11 (Color online) Flight sequence of lunar flyby transfer.

Table 4 Halo orbit maintenance for different amplitudes and frequencies

Amplitude of halo orbit	9000 km		12000 km		15000 km	
maintenance frequency	Half cycle	One cycle	Half cycle	One cycle	Half cycle	One cycle
Mean (m/s)	82.889	205.447	85.493	213.157	87.529	225.497
Standard deviation (m/s)	8.653	29.145	8.513	35.692	8.004	37.244
Maximum (m/s)	102.202	240.996	109.582	276.406	105.196	279.644

initial value to prolong the orbit integration time. Each correction ensures that the satellite can run stably for 1.5 periods and satisfy the velocity constraint. That is, this method carries out orbit maintenance based on three predictive corrections. To ensure convergence and to reduce velocity increment, orbit maintenance restricts the velocity only when passing through the plane without strictly constraining its amplitude.

Based on this control strategy, the amplitude of the running halo orbit will change, and the halo orbit will gradually evolve into a quasi-halo orbit that is still near the mission orbit. Here two types of maintenance frequencies are discussed, half cycle and one cycle. Half-cycle maintenance means the relay satellite will perform a correction at each time it crosses the XZ plane. One-cycle maintenance executes the maneuver for an entire orbit period. Table 4 shows the cost of orbital maintenance in 3 years for different amplitudes of halo orbits under two frequencies. The position error distributed uniformly in three directions is 2300 m (1σ) and the velocity error is 0.06 m/s (1σ). Moreover, the thrust deviation of each maneuver is less than 0.02 m/s (3σ), and the attitude deviation of the satellite is less than 2° (3σ). One hundred Monte-Carlo simulations are performed for each maintenance strategy. One of the simulation results is shown in Figure 12.

According to Table 4, it is found that although half-cycle maintenance requires a greater number of correction maneuvers, its total cost is less than that of one-cycle maintenance. For the halo orbit of amplitude 9000 km, the mean cost of half-cycle maintenance is 82.889 m/s and that of one cycle maintenance is 205.447 m/s. Similar results are obtained for 12000 km and 15000 km halo orbits. Meanwhile, the standard deviation of half-cycle maintenance is considerably less than that of one-cycle maintenance, which means that half-cycle maintenance is less sensitive to the orbital determination error and the control error. Moreover, the maintenance cost increases slightly with an increase in the orbit amplitude. On average, the total cost of orbital maintenance is less than 30 m/s per year.

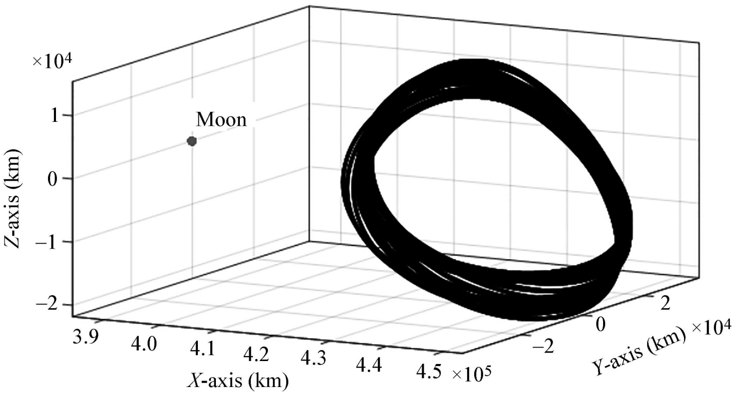

Figure 12 Flight trajectory of relay satellite for three years on Earth-Moon halo orbit.

4 Design of relay satellite communication system

The main purpose of the relay satellite is real-time and delayed relay communications with the Chang'E-IV lander and rover in the forward/backward direction. Other main tasks of the satellite include upstream and downstream communication transmission, and measurement and control operations in collaboration with the measurement and control stations. The details are as follows:

(1) The circumlunar segment. This part supports the real-time and delayed relay communication with the lander on the lunar farside in the forward/backward direction.

(2) Power descent segment. This part supports real-time relay communications with the lander in the forward/backward directions.

(3) Lunar work segment. This part supports forward/backward real-time and delayed relay communications with both the lander and the rover.

Because the monitoring and data transmission systems of the lander and the rover are inherited from Chang'E-III [35], the design scheme of the relay satellite's communication system must be consistent with the existing technical states. Meanwhile, the design must consider the various mission requirements of different segments. In addition, the design of the relay communication system must consider the weight limit of the satellite. To this end, a small, lightweight, and integrated design must be adopted to the extent possible [36–38].

4.1 Selection of relay communication frequency band and design of working mode

Because the lander and the rover use X-band measurement and control, as well as data transmission system, for compatibility with these systems, the relay communication link with the Moon must use the X-band. Two different working modes, namely, real-time relay communication mode and delayed communication mode, can be used when choosing data transmission frequency bands.

(1) Real-time relay communication mode. For communication with the Moon, the satellite uses the X-band. If the data transmission to the Earth is also performed using the X-band, the receiving level backward to the Moon would be far beyond the antenna's dynamic range, resulting in strong interference with the return-to-Moon receiver and preventing it from working. Therefore, the S-band is chosen for data transmission considering the electromagnetic compatibility problems associated with the real-time forwarding mode and the capacity of the existing ground station [39].

(2) Delayed relay communication mode. The same frequency-related problems will not exist if the moon relay communication and data transmission to the Earth are in the time-sharing working state. Therefore, the X-band can be used to increase the data transfer rate and reduce the data transmission time between the satellite and the Earth. It could also serve as a heterogeneous backup for S-band data transmission and improves the reliability of the relay communication system.

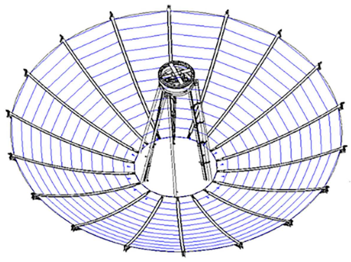

Figure 13 (Color online) Expanded state of high-gain mesh parabolic antenna.

4.2 Selection of relay communication antenna

The caliber of the relay antenna is one of the important factors governing relay communication performance. Especially, the antenna size can determine the backward-to-moon receiving capacity. Therefore, a large-diameter high-gain antenna must be adopted to meet the constraints under all circumstances.

According to the antenna requirements of high gain and low weight, an umbrella antenna measuring with 4.2 m in diameter and equipped with the spring mechanism can be adopted. Internationally, this antenna is of the highest caliber for deep space exploration tasks. The unfolded antenna is shown in Figure 13.

4.3 Design of relay antenna tracking control method

To ensure the performance of the relay link, the relay satellite is equipped with a large-diameter mesh parabolic antenna. The antenna must point to the lander and the rover precisely because of the narrow range of the antenna beam. Meanwhile, owing to the large size and weight of the antenna, it is infeasible to achieve precise steering by using a two-dimensional drive mechanism. Therefore, platform pointing control must be adopted to ensure the high-precision pointing to the lander and the rover.

In addition, the ground communication antenna beams of the relay satellite should coverage at the Earth simultaneously. It is difficult to implement point control by using a drive mechanism. Therefore, the range of the beam angle is set 32° to cover the entire surface of the Earth. An S-band helical antenna is selected to satisfy the communication constraints.

4.4 Redundancy design of relay communication

Redundancy measures must be considered be taken full account of, because the relay communication system, which requires high reliability, is the main part of the relay satellite. A redundancy design is considered in both hardware and software to minimize the possibility of system failure.

The equipment and components for the lunar forward link, lunar return link, and ground communication link as well as the umbrella parabolic antenna, have backups. Meanwhile, in the time-sharing relay mode, the high-caliber parabolic antenna can be adjusted to point to the Earth by performing the satellite's attitude maneuver. Heterogeneous backup of the S-band communication channel can be achieved by X-band high-bit-rate data transmission to ground communication stations.

5 Overall scheme design of relay satellite

According to the mission requirements of the project, the designed life span of a relay satellite should be more than 3 years. Except for the Chang'E-IV relay mission, the relay satellite will carry out other scientific exploration and technical validation tests. The relay satellite includes the platform and the payload. The platform includes satellite management, guidance and navigation, measurement and control, power supply, structure and mechanism, and thermal control. The design weight of the relay satellite is about 400 kg. The long-term power consumption of the satellite is about 400 W. The body-fixed frame is defined, where the Z-axis is aligned with the main axis of the parabolic antenna and the Y-axis is aligned

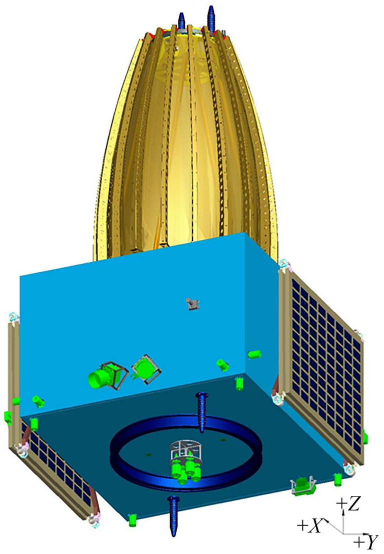

Figure 14 (Color online) Configuration of relay satellite for launch state.

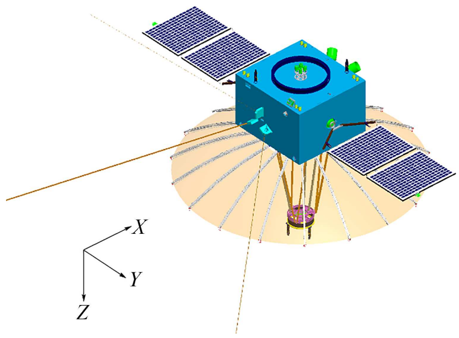

Figure 15 (Color online) Configuration of relay satellite in orbit state.

with the extensional orientation of the solar array. The launch and operation in orbit state of the relay satellite are shown in Figures 14 and 15, respectively.

The payload includes three parts: relay communication load, antenna load, and scientific and technical test load. The relay satellite is equipped with a low-frequency radio spectrum analyzer (LFRSA), infrared spectrometer, and panoramic camera. The LFRSA will be used to detect the low-frequency electric field generated by solar burst and to study the lunar ionosphere. It could receive solar electromagnetic signals and obtain information such as intensity, time-varying phenomena, polarization (polarization) characteristics, and source of low-frequency electromagnetic waves.

The relay satellite employs the zero-momentum control method. The attitude state is provided by a star tracker and a fiber optic gyroscope. Three-axis stability control in the inertia space respective to the Earth, Moon, and Sun can be achieved with a pointing accuracy better than 0.06° and stability better than 0.01°/s. Orbital maneuverability of the satellite is 500 m/s or higher when using a single-element propulsion system. Multiple types of thrusters can be used for orbital maneuvers and orbital maintenance.

The energy system of the relay satellite uses triple junction Ga-As space solar cells, lithium-ion battery pack and Li-ion batteries. It uses a non-adjustment power supply bus and a decentralized power distribution system. The bus voltage can be maintained at 30 $\pm$ 1 V during the non-shadow period.

The ground measurement and control of the relay satellite is performed using a USB measurement and control system and a fixed-pitch, low-gain helix antenna. The lunar relay link, which uses the X-band, adopts an umbrella-shaped parabolic antenna with a caliber of 4.2 m, for sending and receiving data simultaneously. This link uses PCM/PSK/PM modulation in the lunar forward process and BPSK modulation in the lunar backward process. S-band and BPSK modulation are adopted for Earth communication in the real-time working mode. X-band Earth communication can be realized with the parabolic antenna by performing attitude maneuvers in the time-sharing mode. The symbol rate is up to 10 Mbps. The overall flight process of the relay satellite is shown in Figure 16.

6 Conclusion

Relay communication is the key to fulfilling the landing and patrolling task on the lunar farside. In this paper, based on a systematic analysis of the characteristics and the constraints of the relay communication task, we propose an overall design scheme for the relay satellite as well as its flight orbit, which is expected

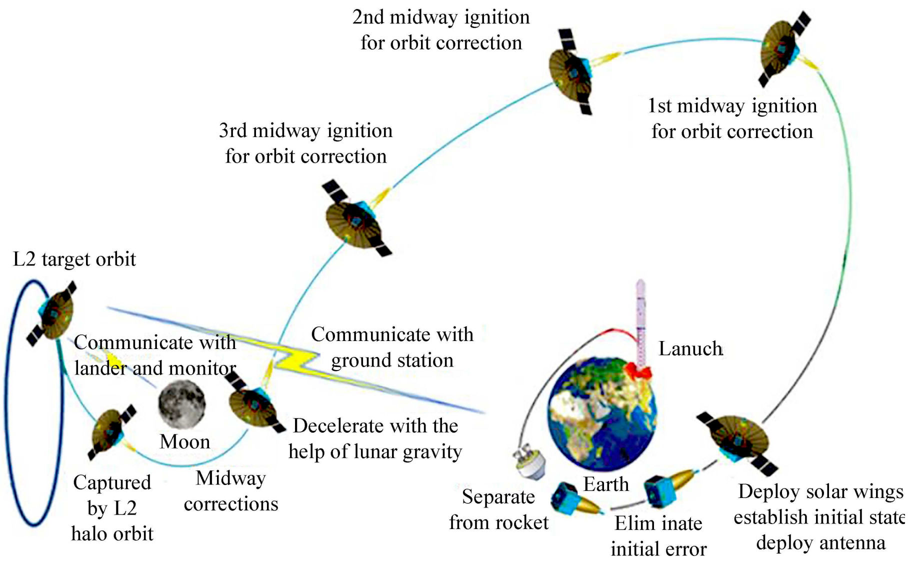

Figure 16 (Color online) Schematic flight diagram of relay satellite.

to be taken as a reference for other tasks such as lunar farside and two-pole landing. Moreover, the paper can be used as a technical reserves for future manned lunar landing or other deep-space exploration tasks.

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