

## Review Article

# Development and Prospect of Chinese Lunar Relay Communication Satellite

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Relay communication satellites play a very important role on the lunar far side and pole areas exploration missions. Queqiao relay communication satellite was developed to provide relay communication support for the lander and the rover of Chang'e-4 mission landing on the far side of the Moon. From entering into the halo mission orbit around Earth-Moon libration point 2 on June 14, 2018, it has operated on the orbit more than thirty months. It worked very well and provided reliable, continuous relay communication support for the lander and the rover to accomplish the goals of Chang'e-4 lunar far side soft landing and patrol exploration mission. Exploration of the lunar south polar regions is of high scientific interest. A new relay communication satellite for Chinese south pole exploration mission is also under study. The system design and on-orbit operation status of Queqiao relay communication satellite were summarized in this paper. The system concept of the relay communication satellite for lunar south pole exploration missions is proposed. Finally, the future development and prospect of the lunar relay communication satellite system are given.

## 1. Introduction

The south pole and the far side of the Moon are ideal places for some scientific investigations. Due to tidal locking, Earth's ground stations can only cover the nearside of the lunar surface. Therefore, the spacecraft on the lunar nearside always have direct line of sight with Earth, whereas those on the far side of the Moon are always invisible from Earth. The landing assets on the far side of the moon would have to rely on relay spacecraft on the orbit to establish communication contacts with Earth ground stations. The landing sites located on the south pole regions of the Moon are in direct line of sight of the Earth about half the time, in general, two weeks on, two weeks off. Additionally, many of the regions of interest, for example, the inside of the impact craters near the pole, often have no direct line of sight to Earth. Thus, for the most of lunar south pole missions, the relay communication satellite is also needed. The relay communication satellite must be in an orbit position convenient to receive data from the spacecraft on the lunar surface and transmit commands to the spacecraft to support the landing, surface activities, and taking off, etc. The development and establishment of a lunar relay communication infrastructure that provides

communications and navigation services for long-term lunar explorations are very important.

This paper first discusses two important issues of the lunar relay communication satellite development, which are the mission orbit selection and relay communication links. Then, the system design and on-orbit operation status of Queqiao relay communication satellite from the orbit insertion to current relay communication support for the lander and the rover of Chang'e-4 mission [1] are summarized. In order to support Chinese south pole exploration mission in the near future, a new relay communication satellite is considered, and the system design concept of this satellite is presented in this paper. Finally, the future development and prospect of the lunar relay communication satellite system are given.

## 2. Mission Orbit Selection

The selection and design of the mission orbit are crucial for the development of the lunar relay communication satellite. The relay communication support for the lunar exploration spacecraft should consider the coverage locations based on the sites of the future lunar bases or surface exploration

missions. In order to meet 100% coverage requirement of the lunar surface, the orbits to be considered for relay communication satellites include the orbits around the moon and the orbits around libration points in the Earth-Moon system [2, 3].

Apart from trying to achieve full communication coverage which is of high priority, the orbit selection and design mainly depend on the mission objectives of relay communication satellites. The first problem that needs to be considered is how to maximize data transferred from the spacecraft on the surface of the Moon back to Earth. With the advancement of lunar exploration, a great amount of scientific data would produce and need to be returned in the future. The visible time of the lunar surface assets and distance to the relay satellite have to be balanced. If a relay communication satellite is placed in a highly eccentric lunar polar orbit with the apolune of the orbit located above the landing site, it can stay over the lunar south pole area for a long time to provide relay communication services, but the transmission data rates would be lower due to power and signal strength losses at the longer distance. On a less eccentric lunar orbit, the relay communication satellite is not in view of the lunar south pole area for a long time, but the communication distance decreases; so, the higher data transmission rates can be achieved. The second problem is how to minimize the  $\Delta v$  requirement, and so the total propellant consumption for injection into the mission orbit and orbit maintenance can be reduced. The third issue is how to minimize the time of flight for the orbit transfer. This can reduce operation cost and decreases the mission risk, but minimizing propellant requirement and minimizing the time of flight are two contradictory requirements. In some cases, a compromise has to be made.

A low altitude orbit around the Moon can provide the relay communication satellites shorter communication paths to surface elements and reduces mass, power, and cost of the onboard communication equipment, while maintaining very high relay communication data rates. A relay satellite in a low altitude lunar orbit will pass over surface elements relatively quickly; so, more satellites would be required than a constellation with high altitude lunar orbit satellites to provide continuous relay communication support.

The relay communication satellite operating on an orbit around Earth-Moon libration point 2 (EML2) has a limited data rate due to very long communication distance between it and the spacecraft on the lunar surface. But for the spacecraft on the far side of the Moon, one relay communication satellite on the orbit around EML2 can provide continuous relay communication coverage. This is favorable for the lunar far side landing exploration missions. However, the relay communication satellite operating on the orbits around Earth-Moon libration points has to employ larger spacecraft with higher power amplifier and larger aperture antenna to achieve enough communications data rate at a longer distance from the Moon.

The relay communication satellite constellation using the large elliptical orbit around the moon could supply full coverage of the lunar south pole and limited coverage for other lunar surface areas. While a relay communication satellite

constellation in an inclined and polar circular lunar orbit with low to moderate altitudes can achieve full communication coverage, in the meantime, the communication distance is short, and the cost for high data rate communication can be reduced greatly. With the rapid development of miniature technology, in the future, by means of a large number of inexpensive microsattellites, operating at low lunar orbits, a low cost relay communication constellation can be established to provide cost-effective relay communication services.

### 3. Relay Communication Link Consideration

The relay communication satellite system provides the means of relaying data between the spacecraft on the lunar surface and the ground stations on Earth. Typically, four different relay communication links should be established:

- (1) Commands and uplink data from the Earth ground stations to the relay communication satellite
- (2) Commands and uplink data from the relay communication satellite to the spacecraft on the lunar surface
- (3) Data from the spacecraft on the lunar surface to the relay communication satellite
- (4) Data from the relay communication satellite to Earth ground stations

The relay communication links are quantified by link budgets which are used to size the antennas, estimate data rates, and determine power requirements of the relay communication system. For the relay communication satellites operating on the distant orbits around the Earth-Moon libration points, communication link design presents a significant challenge. The relay communications system must have adequate transmission power and large antenna aperture.

Two kinds of relay communication modes can be selected. One is the transparent relay transfer mode, and the other one is the regenerative relay transfer mode. Compared with the regenerative relay transfer mode, the transparent relay transfer mode (bent pipe mode) is flexible and is capable of supporting a wide range of user signal format, but it present higher requirements for the supporting capabilities of the ground stations. By means of coding technology, regenerative relay transfer mode can provide extra link gain, which is favorable for the situation with limited onboard resources. Each relay communication mode has its advantages and disadvantages and which mode is better choice depends on the specific requirements and constraint conditions. Therefore, the trade studies should be performed before determining the relay communication mode. Hybrid modes covering both the transparent relay transfer, and the regenerative relay transfer functions maybe a better choice for some missions.

Spectrum utilization is another important issue of the lunar relay communication system design, which involves multiple frequencies and bandwidths. Currently, for the tracking, telemetry, and command (TT&C) links between the lunar relay satellite and Earth ground stations, the Unified X-band

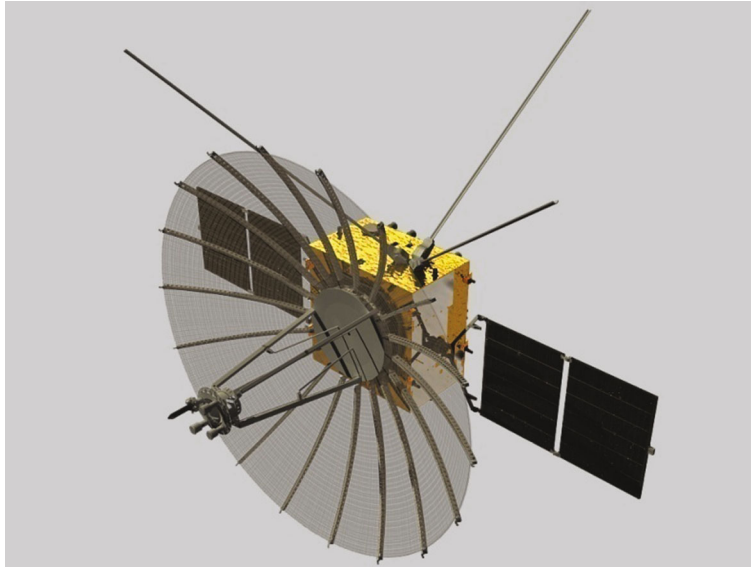


FIGURE 1: On-orbit configuration of Queqiao.

(UXB) system is used for most missions. It can save significant mass, power, and volume over the Unified S-band (USB) system. X band is only suitable for the TT&C links with a data rate of not more than 10 Mbits/s. The maximum uplink data rate requirement for future human lunar missions could be more than 20 Mbits/s so, Ka band can be used for TT&C links with high data rates. For the high data rate relay communication links between the lunar surface spacecraft, relay satellite links, and relay satellite to Earth links, Ka band is suggested. For the low data rate relay communications links, S band can also be used. Because the UXB system is used for the TT&C links of most current lunar missions, in order to be compatible with the UXB TT&C system, X band is a better choice for current relay communication links between the lunar surface spacecraft and relay satellite. If the user spacecraft uses Ka band for the TT&C links in the future, Ka band should be used for the relay communication links between the lunar surface spacecraft and relay satellite. The specific frequency band selection for each communication link should be considered thoroughly. The potential RF inference between different links should be avoided and mitigated through coordinated allocations. Delicate EMC design and full EMC test evaluation are crucial for ensuring the normal work of the relay communications system.

In the long run, for some lunar missions with high data rate requirements, the optical communication is a better choice, especially for the relay communication links between the spacecraft on the lunar surface and relay satellites. The high data rate communication links for deep space and lunar vicinity mission should be established by means of the optical communication system.

#### 4. Queqiao Relay Communication Satellite for Chang'e-4

**4.1. Mission Overview.** Chang'e-4 is a Chinese lunar far side landing and patrol exploration mission, which is composed

of a lander, a rover (named as Yutu-2), and a relay communication satellite (named as Queqiao). For the lander and the rover working on the far side of the Moon, communication links with ground stations cannot be established without a relay satellite. So, the development and deployment of a relay communication satellite are the prerequisite for accomplishment of the Chang'e-4 mission.

As an important and innovative part of Chang'e-4 mission, the Queqiao relay communication satellite was developed and launched into the orbit half a year before the launching of the lander and the rover. It can provide real-time and delay-time relay communications to the lander and the rover operating on the lunar far side to maintain their communication contacts with Earth stations.

A halo orbit around the Earth-Moon libration point 2 is an ideal location for lunar far side relay communications, which permit continuous communication coverage at a cost of longer transmission distances. Queqiao is the first spacecraft in the world to run on a halo orbit around the Earth-Moon libration point [4]. Up to now, it has operated on the mission orbit more than thirty months and provided reliable relay communication support for the lander and the rover of Chang'e-4 mission.

**4.2. System Design [5].** Queqiao is a small spacecraft and was developed based on CAST100 small satellite platform of DFH satellite Co., Ltd. and experiences from other Chinese lunar missions. The platform is composed of six subsystems: structure and mechanisms, thermal control, housekeeping and onboard data handling (OBDH), guidance navigation and control (GNC), TT&C, and power supply. The payloads include relay communication subsystem, antenna subsystem, and scientific and technology demonstration subsystem.

Figure 1 shows the on-orbit configuration of Queqiao. The major technical performance parameters of Queqiao are listed on Table 1.

TABLE 1: Major technical performance parameters of Queqiao relay satellite.

Item	Major parameters
Orbit	Halo orbit around EML2 with Z-amplitude of 13000 km
Platform	CAST 100 small satellite platform
Mass/kg	448.7
Size/mm <sup>3</sup>	1400 × 1400 × 850 (satellite body)
Attitude control	Three-axis stabilized zero-momentum control Pointing control accuracy: better than 0.06° Pointing stability: better than 0.005°/s
Propulsion	Hydrazine propulsion system with two 70 L tanks Four 20 N thrusters and twelve 5 N thrusters Carrying 105 kg propellant can provide more than 550 m/s $\Delta v$
Power	Output power of solar array: >780 W Capacity of the storage battery: >45 ah
TT&C	USB + VLBI Date rate: 1000 bits/s (uplink)/2048 bits/s (downlink)
Relay communications	Four links between Queqiao and rover/lander (X band), one link between satellite and earth (S band, X band as backup) A 4.2 m diameter parabolic antenna is used for communication with the rover and the lander A spiral antenna is used for S band data transmission Data rate: 125 bits/s (from Queqiao to rover/lander) 1.4/50/280/555 kbits/s (from lander to Queqiao) 0.7/140/285 kbits/s (from rover to Queqiao) 1/2/4/10 Mbits/s (from Queqiao to earth stations, S band or X band)
Lifetime	More than 3 years

The GNC subsystem is responsible for maintaining Queqiao's attitude, solar array orientation, and high gain relay communication antenna pointing throughout the mission. It also controls and monitors the propulsion system. In the nominal control mode, two star sensors and two inertial measurement units (IMU) which contain both accelerometers and gyroscopes are used to provide fine attitude determination. The primary control mechanism onboard Queqiao is four reaction wheels. Their desaturation is performed with thrusters.

The propulsion system is required to provide Queqiao with the necessary  $\Delta v$  to insert into and maintain mission orbit. A monopropellant hydrazine blow-down system was adopted by Queqiao. It consists of a series of thrusters, tanks, propellant, latch valves, and pipelines. The propellant is stored in two equally sized tanks with 70 L volume and can provide propellant to the 16 thrusters.

The power supply subsystem is responsible for the generation, storage, and distribution of electric power onboard Queqiao. During periods of sunlight, the power supply subsystem would employ solar arrays using triple-junction GaAs solar cells (780 W output power can be provided at EOL) to generate electric power, and a 45 Ah Li ion storage battery was carried to provide power in the shadow period. The electric power would be distributed along an unregulated 28 V power bus and would be converted to usable voltages for each subsystem.

Because the relay communications distance is as far as 79000 km, in order to achieve enough high gain to ensure required relay communications capability, a large size relay communication antenna with an aperture of 4.2 meter, shaped like an umbrella, was developed, as shown in Figure 2. It is the largest communication antenna ever used in world deep space exploration missions and can provide high gain with more than 44 dBi at X band.

This large aperture antenna has very narrow beam angle; so, the 4.2 m relay antenna beam must be continuously pointed to the lander and the rover with high accuracy to meet the relay link capability requirements. Taking advantage of the characteristics of the mission orbit around Earth-Moon L2, the antenna was fixed to the top panel of Queqiao, and its beam pointing was controlled by means of the attitude control of the satellite, which avoided the use of tracking mechanisms onboard satellite. GNC controls the antenna pointing according to the uploaded landing location of the lander as well as Queqiao's orbit prediction information based on the high accuracy orbit measurement and determination technologies.

For the S band data transmission link, a fixed spiral antenna is used, with a gain of more than 6dBi under the beam angle of  $\pm 32^\circ$ , which can cover ground stations during relay communication with the lander and the rover to ensure they can work concurrently.



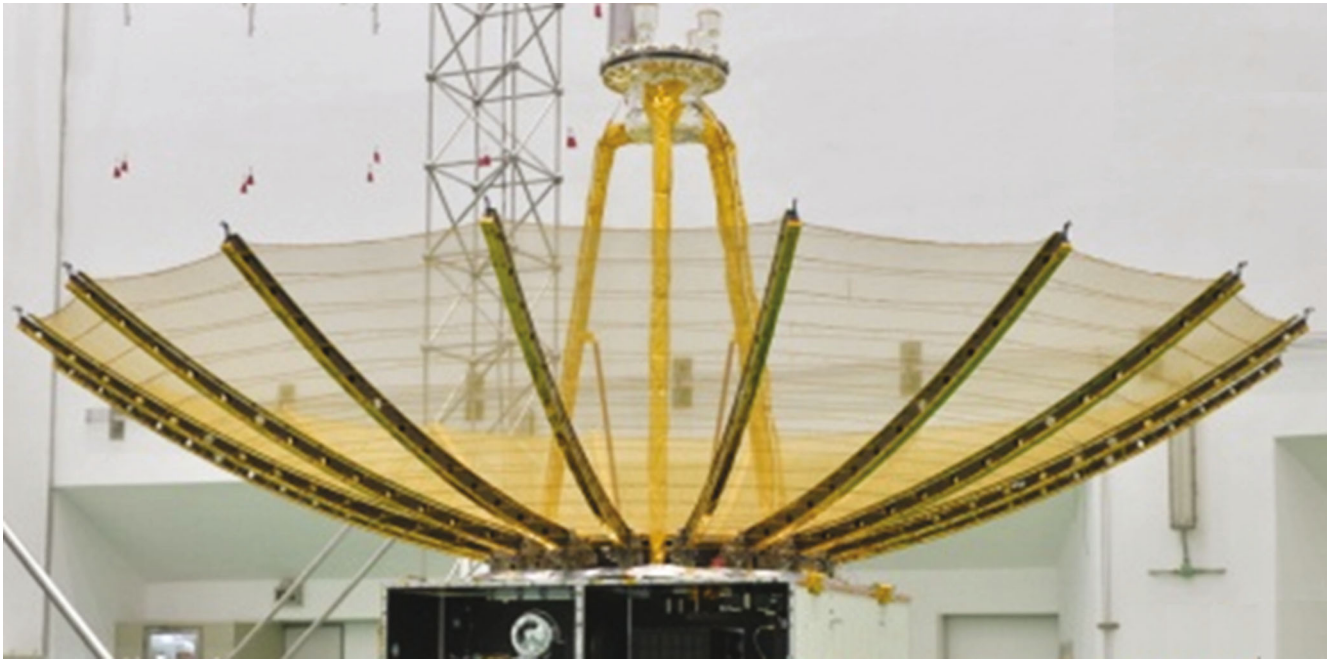


FIGURE 2: Relay communication antenna with 4.2 m aperture.

**4.3. Orbit Parameter Design [4].** In order to keep continuous visibility with the lander and the rover operating at the Aitken basin area on the far side of the moon, the final determination of specific orbit parameters took the relay communication coverage, communication distance, eclipse time, etc. into considerations.

Due to the unstable dynamics of the orbits around Earth Moon libration points, maneuver navigation and execution errors can cause the actual trajectory of Queqiao to diverge from its desired trajectory over time. For this reason, if Queqiao wants to stay on the mission orbit for several years, some small and repeated propulsive orbit maintenance maneuvers have to be made to maintain the trajectory. The cost for orbit maintenances is also an important factor that needs to be considered for the selection of the orbit parameters.

After comprehensive trade and analysis, a southern halo orbit around EML2 with Z-amplitude of 13000 km was selected for Queqiao. On this orbit, the longest distance to the Moon is 79000 km, and the shortest one is 47000 km. This orbit has an orbital period of fourteen days, making two revolutions in each lunar “day.”

**4.4. Relay Communication Payload Design [6].** Queqiao’s relay communication subsystem can support two-way communication with the lander and the rover, sending commands and data to the lander/the rover, as well as receiving science data and telemetry from the lander/the rover. The data from the lander/the rover, combined together with Queqiao’s own scientific data and telemetry data, are sent back to Earth ground stations. The final relay communication architecture was determined in terms of communications frequencies, communications data rates, size, mass, power, lifetime requirement, reliability, and the constrained conditions from ground stations. The block diagram for the relay communication payload is shown in Figure 3.

Queqiao was designed specifically for the Chang’e-4 mission. Its interface has to be compatible with existing status of the lander and the rover, which use X band for the command, telemetry, and data transmission; so, X band has to be adopted for the relay communication links between Queqiao and the lander/the rover. In order to avoid RF interference with X band relay communication links which have both large transmission power and high reception sensitivity, the unified S band (USB) system was adopted for TT&C of Queqiao, and the S band data transmission system was used for the data transmission between Queqiao and the ground stations.

Unlike the typical data relay satellites operating on the Earth orbit, which adopts the transparent forwarding mode, the regenerative forwarding mode was adopted for Queqiao. This can provide extra link gains by means of coding and reduce the resource requirements. This is very important for Queqiao: because of the long relay communication distance and very limited onboard resources, gain can be increased about 7 dB through coding.

Both the real-time and delayed-time relay communications using store and forward method can be provided for the lander and the rover of Chang’e-4 mission. If Queqiao can be seen by a ground station, the real-time mode will be used. In most time of the on-orbit operation, real-time relay mode was used. If there is no ground station that can access Queqiao, the delay-time relay mode is used. Queqiao stores the data onboard first, then forwards it to ground stations when access becomes available.

Queqiao is able to provide the four relay communication links for the lander and the rover simultaneously, as shown in Figure 4. By utilizing different frequencies and the RF matrix switch, each of the four relay communication links can use the same 4.2 m high gain parabolic antenna.

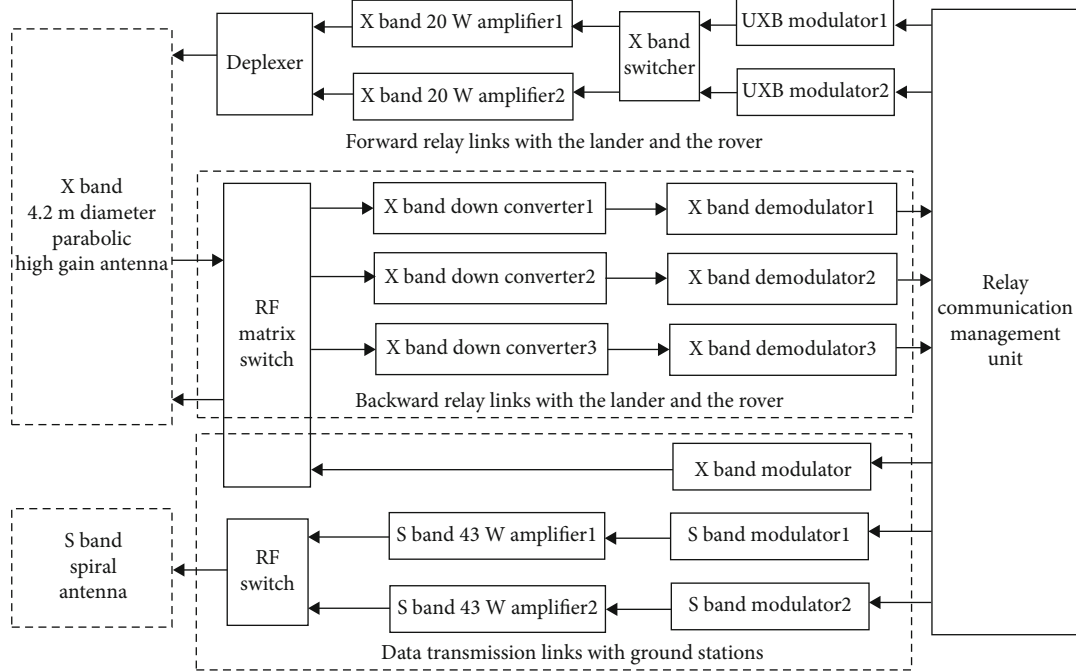


FIGURE 3: Block diagram for relay communication payload.

The relay communication data can be transmitted at different frequencies and data rates under different working modes, as shown in Table 1. There is a relay communication management unit onboard Queqiao to perform, manage, and control to the relay communications, process relay data, and provide interfaces with other onboard subsystems. In addition, this unit carries a mass storage with 512 Gbits volume to store the data from both the lander/the rover and Queqiao itself.

There are two relay links between Queqiao and the lander. One is a forward link and the other one is a backward link. There are two similar relay links between Queqiao and the rover. For each forward link, a 20 W X band solid-state amplifier was used to produce the transmit power needed to meet the link performance requirement. According to the antenna diameter and the transmit power, the effective isotropic radiated power (EIRP) of Queqiao is more than 55 dB. Queqiao can forward commands to the lander and the rover simultaneously with a data rate of 125 bits/s. The link margin is more than 5 dB. After receiving the command data from housekeeping and OBDH subsystem of Queqiao, the command for the lander and the command for the rover are identified and checked. Then, they are sent to the corresponding modulator to modulate and transmitted to the lander and the rover by means of amplifiers and relay communication antenna.

The backward relay links of Queqiao have a G/T value of more than 15 dB/k, which can meet the required gain over system noise temperature requirement. The data from the lander and the data from the rover also can be processed simultaneously. After receiving the return data from the lander and the rover, through down frequency converting, the signals are sent to the corresponding demodulator to perform synchronization, demodulation, and decoding. Then,

the data is written in a unified format and sent to the relay communication management unit. The backward relay links can be established with more than 3 dB margin. If a small directional parabolic dish with modest gain was used on the lunar surface, a data rate of 285 kbits/s for the rover and 555 kbits/s for the lander could be achieved. If using an omnidirectional antenna on the lunar surface, the data rate is only 700 bits/s for the rover and 1400 bits/s for the lander. It is used only for the relay of telemetry data.

Because of long communication distance as well as the limitation of antenna gain and transmit power, the EIRP of the lander and the rover is quite small. For the low data rate backward links, the EIRP of the lander is about 0 dBW, and the EIRP of the rover is about -1 dBW. The lowest signal level received by Queqiao is less than -136 dBm. It is a critical technology for Queqiao to be able to demodulate the backward link data effectively and reliably under extremely low signal level as well as large frequency deviation and high Doppler dynamics. The required demodulation performance was finally achieved through delicate electric circuit design and an effective demodulation algorithm which combined fast Fourier transformation (FFT) with least-square estimate of frequency deviation, carefully selecting the signal with extremely low noise.

The forward relay links adopted PCM/PSK/PM modulation. The modulation used for backward relay links and data transmission link to ground stations was BPSK with coding, which can provide a coding gain of about 7 dB and can improve the bit error rate (BER) of the link.

For the data transmission link between Queqiao and ground stations, an S band data transmission system was used, which is composed of two modulators, two 43 W solid state amplifiers, an RF switch and a filter. The data rates can also be varied with a maximum data rate of 4 Mbits/s. The S

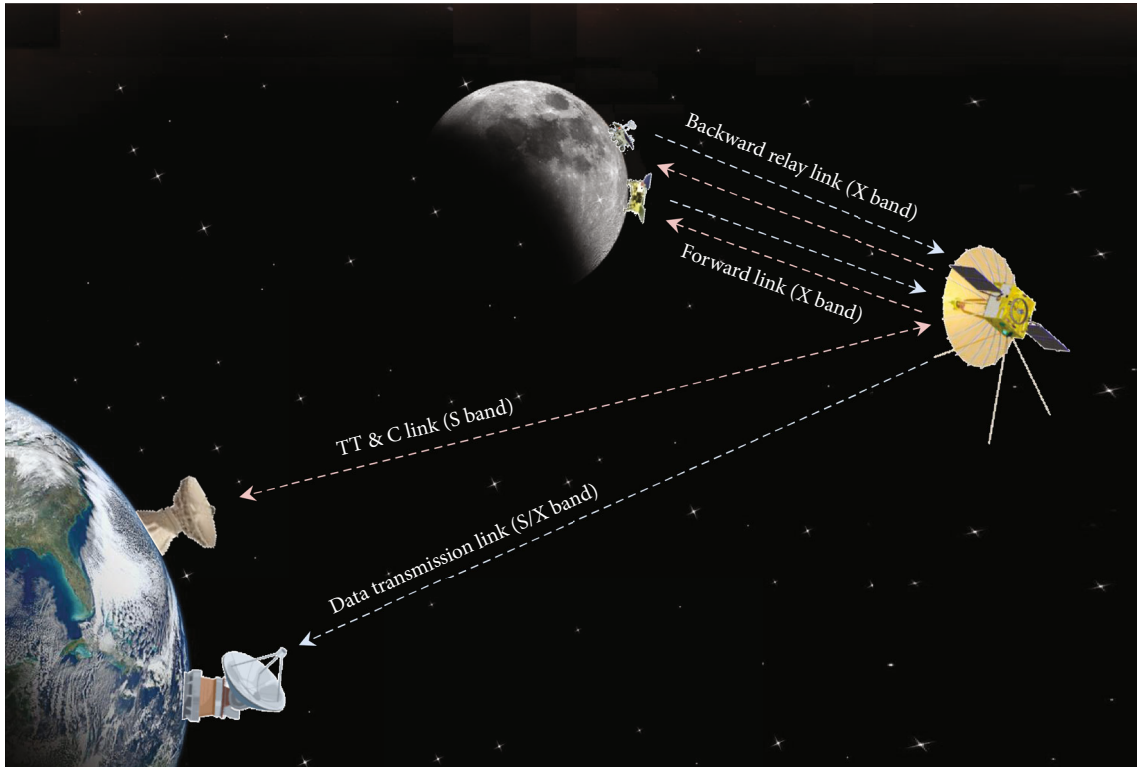


FIGURE 4: Relay communications links for the Chang'e-4 mission.

band data transmission can work with relay communication links simultaneously. To provide a backup data transmission capability, an additional X band data transmission link using the same 4.2 m parabolic antenna can be established in the event that failures occur with the S band data transmission system. Its data rate can be more than 10 Mbits/s.

**4.5. Flight Procedure.** After two and half year's development, on the morning of May 21, 2018, the Queqiao relay communication satellite was launched at the Xichang satellite launch center. It successfully separated from the CZ-4C launch vehicle after 1530s' flight, as shown in Figure 5. One minute later, two solar arrays were unlocked and deployed to provide solar power for the satellite. 25 minutes later, the umbrella-like relay communication antenna with 4.2 m diameter was unlocked and deployed to full size. Then, the normal flight attitude of the satellite was established, and the journey to the moon started. The flight trajectory of Queqiao is shown in Figure 6.

After separating from the launch vehicle, Queqiao was placed on a lunar swing-by trajectory that takes longer time than a direct transfer but can save energy and reduce the propellant requirements and the mass of the spacecraft. On the evening of May 21, the midcourse correction maneuver was performed to secure Queqiao's right trajectory to the Moon. On the evening of May 25, as the most critical flight event on the journey to the mission orbit, the perimoon braking was performed successfully at about 100 km above the moon surface, assisted by a 203 m/s impulse burn given by four 20N thrusters, with a burn time of 912 s. This swing-by maneuver threw Queqiao toward the mission orbit around

Earth-Moon L2 point, about 65000 km distance from the moon. On June 14, 2018, by means of a 66 m/s  $\Delta v$  maneuver, Queqiao was captured and entered into its final halo orbit according to designed orbit parameters. The perimoon braking and the captured halo mission orbit are shown in Figure 7.

## 5. On-Orbit Operation Status of Queqiao [7]

**5.1. On-Orbit.** After entering into the final halo mission orbit, a series of on-orbit tests were performed for Queqiao. By July 2018, the tests of platform were completed, including the tests for GNC, power, TT&C, OBDH, and thermal control. Test results showed that the performance of the platform can meet the mission requirements.

Because the narrow beam angle is used, the pointing accuracy of the relay communication antenna is very important for the accomplishment of relay communication mission. From June 16 to July 6, 2018, the pointing performance of the relay communication antenna was tested by means of the 65 m aperture ground antenna located in Shanghai. The onboard relay communication antenna was pointed to the ground test antenna through sweeping controls realized by means of the GNC system onboard Queqiao. In the meantime, Queqiao's forward relay communication link sent single-carrier signals to the ground antenna, and the ground equipment performed measurements on the received signals, from which the pointing error of the relay communications antenna could be calculated. Results from seven tests showed that the pointing error of the relay



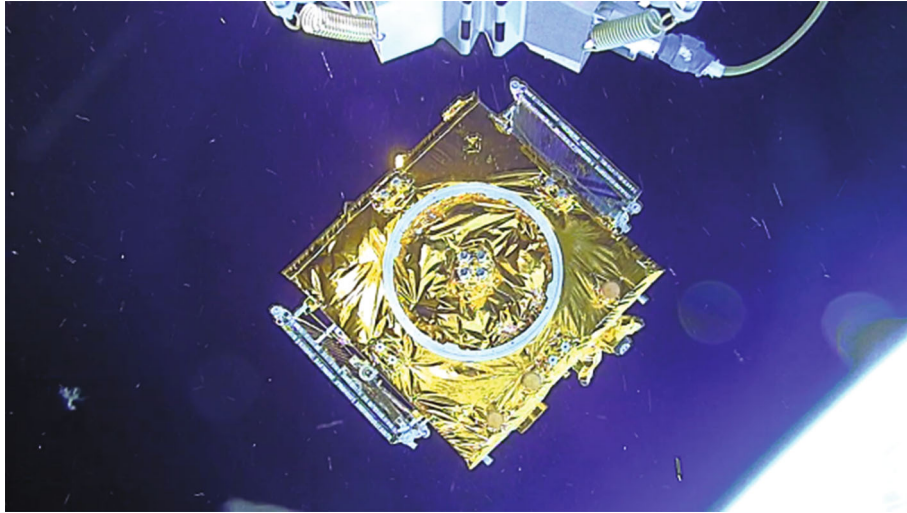


FIGURE 5: Image of Queqiao just after separation from the CZ-4C launch vehicle.

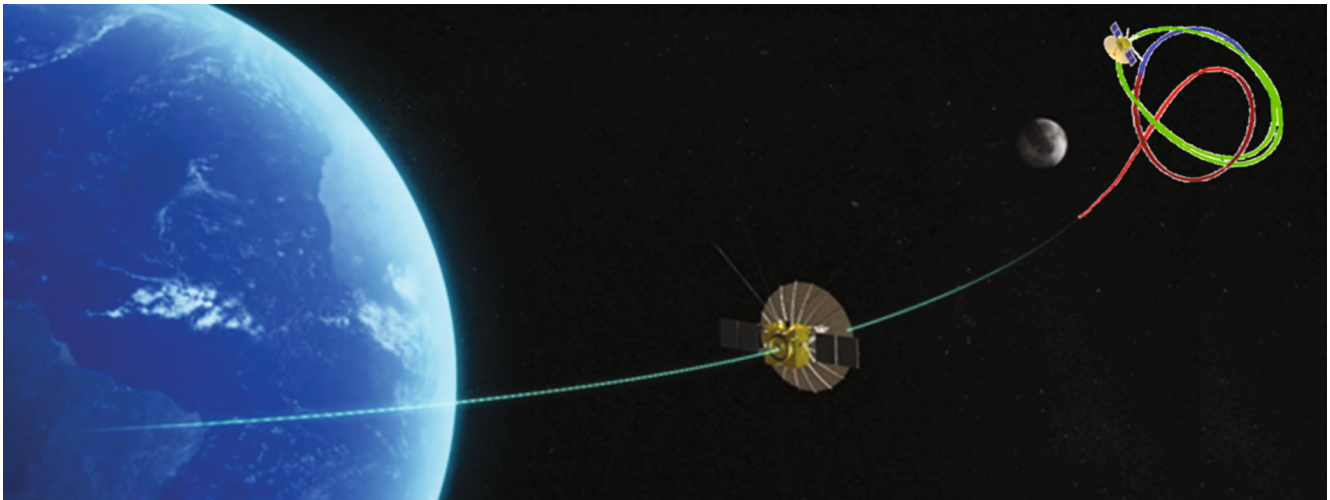


FIGURE 6: Flight trajectory of Queqiao.

communication antenna is less than  $0.1^\circ$ , better than the requirement of  $0.2^\circ$ .

Before launching of the lander and the rover, the relay communication links were tested in July 2018. The relay communication links between Queqiao relay communication satellite on orbit and the electrical models of the lander and the rover on ground were established successfully. This test scenario is very similar to the working status of the lander and the rover on the far side of the moon. The major difference is the longer communication distance, and it was compensated during tests. Detailed tests were performed on the forward relay communication link and the backward relay communication link. Both links worked well, and test results showed that the performance of the relay communication system of Queqiao can meet the mission requirements.

After the lander and the rover were launched and entered into the Moon orbit, relay communication links were tested again in December 2018. The forward relay communication

link with 125 bits/s data rate and the backward relay communication link with 1.4 kbits/s data rate between Queqiao on the halo orbit and the lander in the lunar orbit were established successfully. The results from four tests showed that the forward relay link and the backward relay link worked well. This meant that Queqiao had the capability to provide relay communication support for the lander and the rover to maintain contact with the Earth stations during their landing, separation, and surface operations.

*5.2. Relay Communication Support during the Descent and Landing Phase.* According to schedule, Chang'e-4 probe performed soft landing on January 3, 2019. Before the start of the descent procedure, the forward relay communication link and the backward relay communication links with 1.4 kbits/s data rate were established normally. During the 690 s descent sequence, Queqiao kept tracking and pointing relay communication antenna to the Chang'e-4 probe on its descent trajectory, and the relay communication links worked



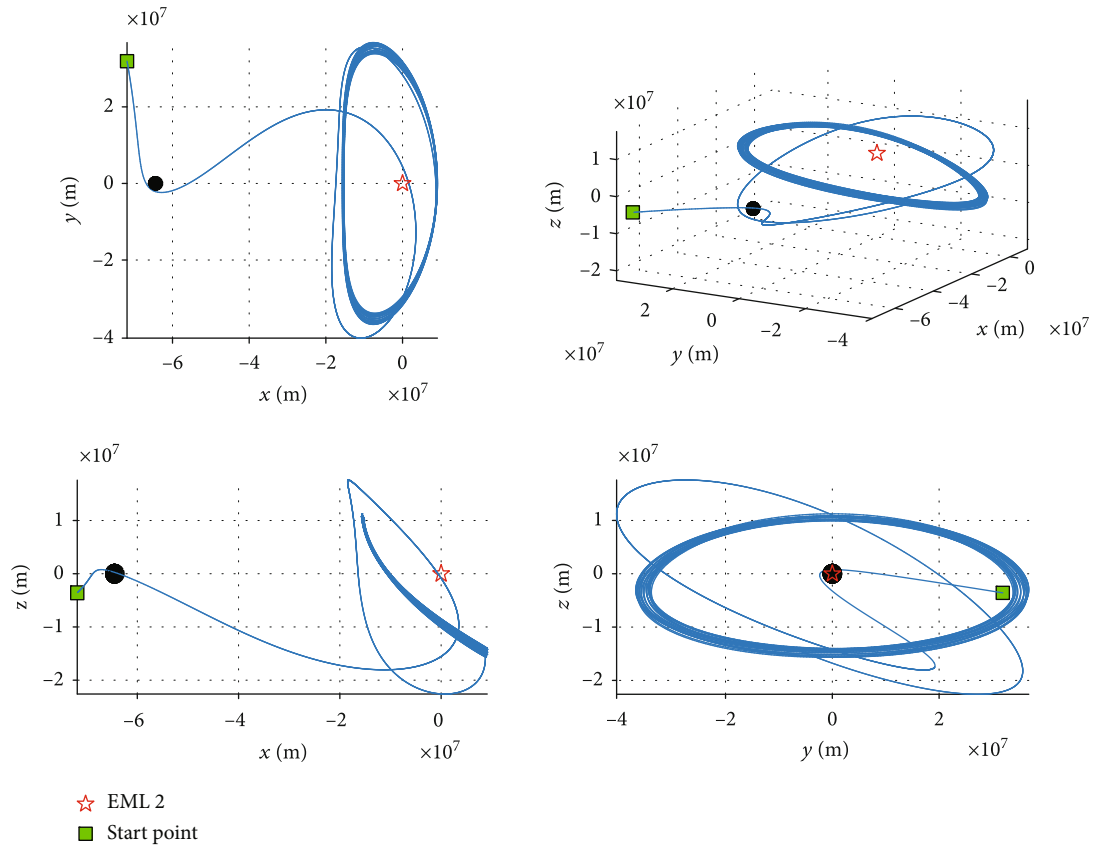


FIGURE 7: Perimoon braking and the captured halo mission orbit.

continuously. The onboard working status of the lander was transmitted to the ground control center in real time. When the descent camera started working, its images were also sent to ground stations by the backward relay link with the data rate of 50 kbits/s, as shown in Figure 8.

**5.3. Relay Communication Support during the Surface Operation Phase.** After the goal of soft landing was accomplished with the support of Queqiao, the ground stations sent commands to unlock the rover, then the rover separated from the lander. The relay communication link with the rover was also established successfully. Under the control from the ground stations, the rover walked down along the ladder to the lunar surface smoothly, becoming the first rover to walk on the far side of the Moon.

Via Queqiao, the lander and the rover were controlled to work on the far side of the Moon by ground stations. The images, telemetry, and scientific data from the lander and the rover were obtained continuously. Up to now, all the relay communication links at different data rates and frame lengths have been used. They all worked well.

By the end of 2020, the lander and rover had worked on the Moon for more than twenty-five lunar days. The Yutu-2 rover has walked more than 600 m distance on the lunar surface. During the lunar night, they went into sleep mode. When the lunar day came back, they woke up and started working via Queqiao. During the lunar day, all the scientific instruments onboard the lander, and the rover are switched

on and perform science explorations. Queqiao provides relay communication support for awakening and sleeping, performing patrol and scientific observations. Ground stations send commands and uplink data to Queqiao first with a data rate of 1000 bits/s. Then, the relay satellite transfers the commands to the lander and the rover, respectively, through forward relay links with a data rate of 125 bits/s. Queqiao receives the telemetry and scientific data from the lander and the rover through backward relay links with data rates of 555 kbits/s and 285 kbits/s, respectively. After demodulation of the received data, the encoding and framing are performed together with the data produced by Queqiao itself, and then the combined data are sent to ground stations by means of the S band data transmission system with data rates of 2 Mbits/s or 4 Mbits/s. This process is shown in Figure 9.

The on-orbit test and operation results confirmed that Queqiao provided continuous and reliable relay communication support while meeting all of the link requirements. All link gain margins are more than 3 dB.

Through two years explorations, a great amount of valuable scientific data was received first by the X band relay communication links of Queqiao and then sent back to ground stations by S band data transmission link. Both Chinese and international scientists have made some analysis and research on the retrieved data and have produced some valuable scientific results. The longer the operation life of Queqiao, the more scientific outcomes can be achieved for the lander and the rover. With the rover roaming more areas

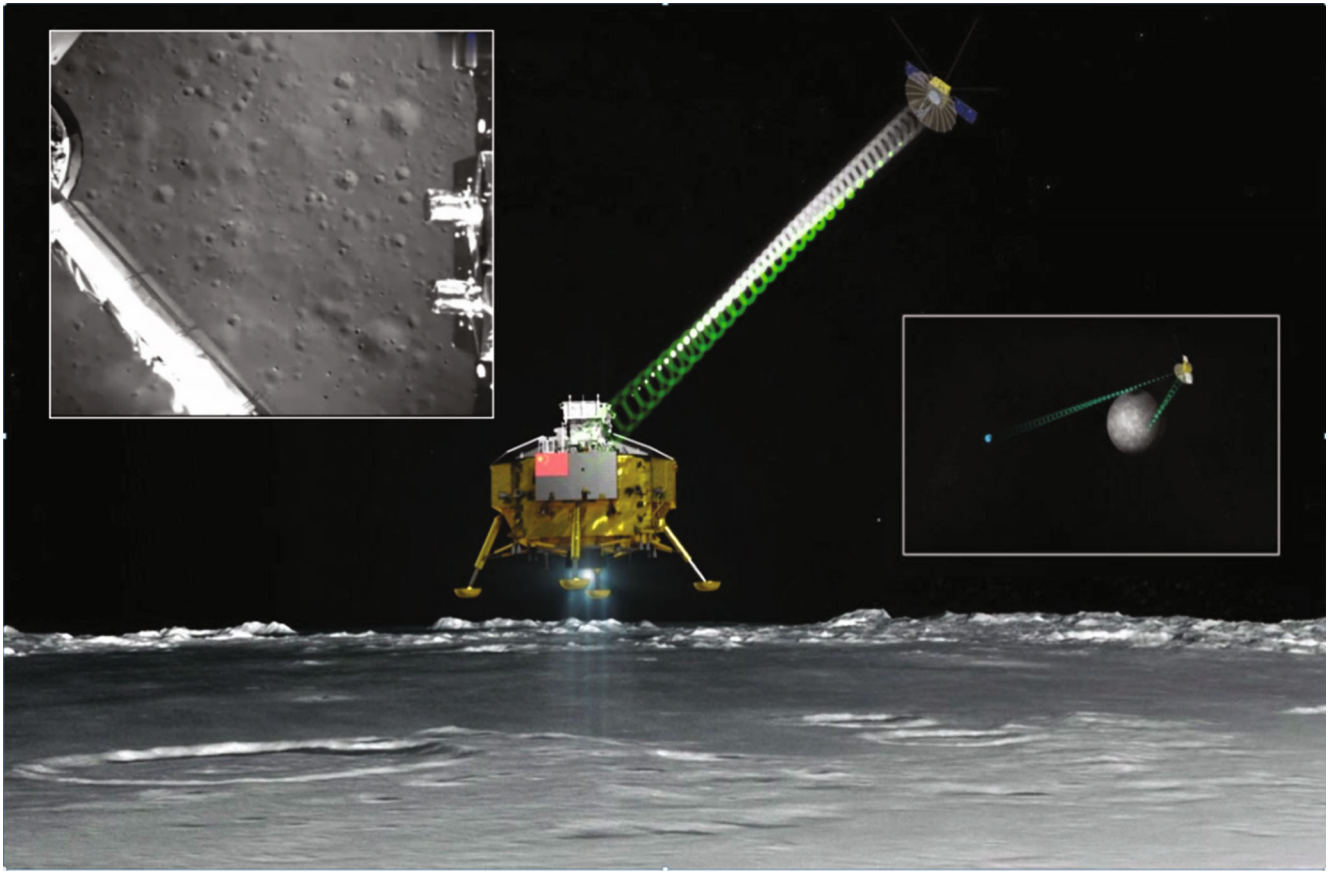


FIGURE 8: The descent sequence of the lander and the rover under the support of Queqiao (the picture on the left top was taken by the descent camera of the lander). Under the support of Queqiao, the lander carried the rover and landed successfully on the surface of the far side of the Moon. After landing on the Moon, the camera on the lander took the first near-distance picture of the lunar far side surface, and the picture was sent back to ground stations via Queqiao.

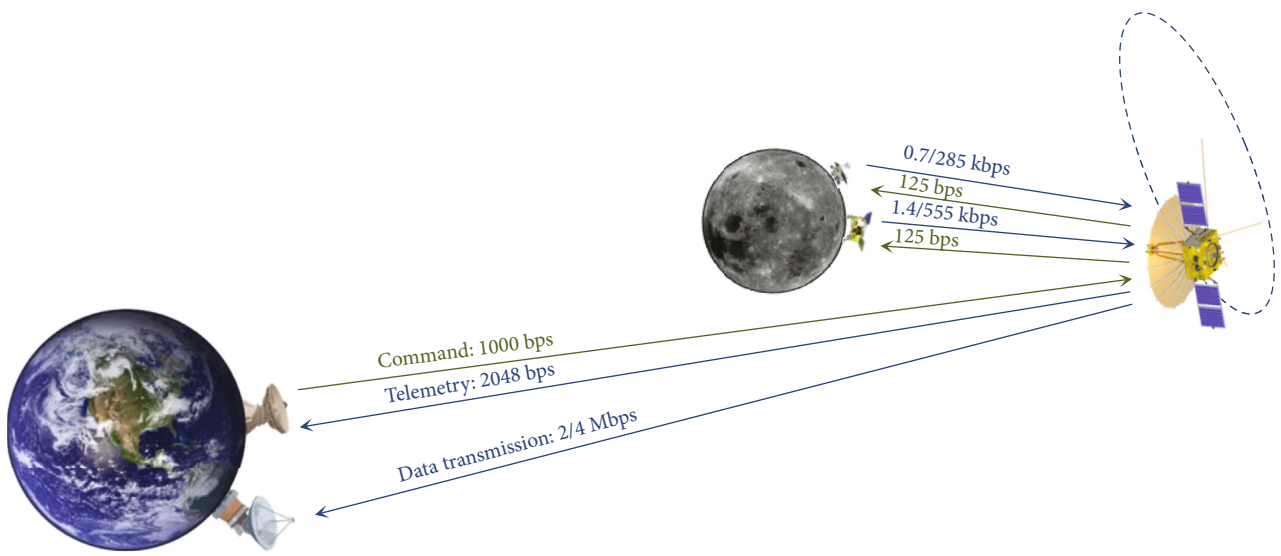


FIGURE 9: Relay communication links used in lunar surface operations.

around Von Karman crater in the South Pole Aitken basin, it is believed that more scientific outcomes can be achieved in the future.

5.4. *Mission Orbit Maintenance.* Mission orbit maintenance is a very important and routine work for the on-orbit operation management of Queqiao. Queqiao operates on a halo

mission orbit around Earth-Moon libration point 2. The libration point orbits near colinear locations are inherently unstable and must be controlled regularly after some flight time.

While a variety of orbit maintenance strategies for libration point orbits have previously been realized for other missions, most of them were used for applications in the Sun-Earth system. Only ARTEMIS spacecraft [8] and Chang'e-5 T1 spacecraft have entered into trajectories near the Earth-Moon libration points, but the orbit type they used is the Lissajous orbit. The orbit type selected by Queqiao is the halo orbit, and it is used for the first time in the Earth-Moon system. The maintenance for it is more complicated. Moreover, in order to ensure the relay communication performance, there are more strict size and orientation requirements on the halo mission orbit.

Queqiao was launched with a dry mass of 343.7 kg and carried 105 kg of hydrazine propellant. The transfer to the halo mission orbit spent about 52.6 kg propellant. At the beginning of the orbit maintenance phase, the remaining propellant mass was 52.4 kg.

Up to now, the Queqiao relay satellite has operated at the halo mission orbit more than thirty months. By December, 2020, 97 orbit maintenance maneuvers in total have been performed. In average, the orbit maintenance maneuver was performed about every 9 days. The propellant used in each orbit maintenance is only about 120 g. All the orbit maintenances were completed successfully and made sure that the halo orbit can meet the requirement.

According to the original design, the  $\Delta v$  budget for maintenance maneuver requirements is about 36 m/s each year. During the on-orbit operation phase, in order to achieve longer operation life for Queqiao, the strategy of orbit maintenance was made with the goal of minimizing the propellant cost. The continuous improvement control strategy was used for the orbit maintenances of Queqiao [9]. By means of this control method, the maintenance maneuvers were performed to minimize the  $\Delta v$  requirements.

According to real orbit maintenance results in the first two years, the spent  $\Delta v$  is about 20 m/s per year in total. It is only about half of the anticipated orbit maintenance cost. Currently, the remaining propellant can still support Queqiao to operate at its halo mission orbit for more than 5 years.

## 6. The System Concept of the Relay Satellite for Chinese South Pole Mission

After the lunar near side and far side landing exploration missions, the south pole of the Moon will be the next objective for Chinese robotic lunar explorations. In order to make better use of the moon resources, as the first step, the detailed investigation of the moon's south polar regions will be performed through comprehensive exploration of resources and environment by means of orbiter, lander, rover, hopper, etc. [10]. Its major scientific objectives include the characterization and water ice exploration of the south polar regions of the moon.

Since the spacecraft landing at lunar south pole areas has long time without direct access to Earth, it is impossible to

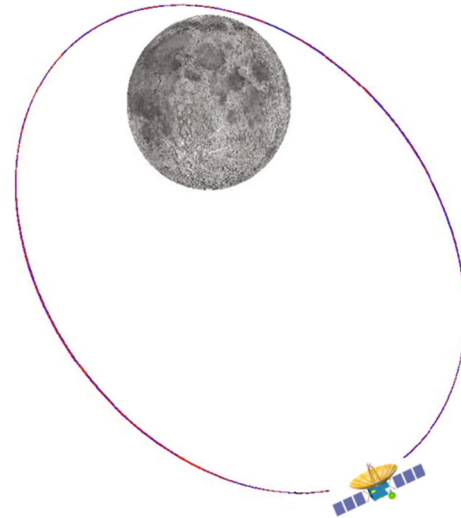


FIGURE 10: Operation orbit of relay satellite for lunar south pole mission.

effectively communicate with surface elements in the south pole areas of the Moon without a dedicated relay communication satellite.

In order to support future Chinese lunar south pole exploration missions, a relay communication satellite system concept is currently under studied. This relay communications satellite will emphasize flexibility to use and scalability to respond to increasing relay communication service requirements. It will provide relay communication for multiple users located at lunar south polar regions.

Driving requirements for this relay communication satellite include the following aspects:

- (1) Support multiple missions and multiple spacecrafts on the lunar south pole areas
- (2) Provide as much communication coverage as possible to the lunar south pole areas
- (3) Provide X band relay communication links to user spacecraft on the lunar surface at south pole areas
- (4) Provide forward communication link service and backward communication link service to a maximum of 10 simultaneous users
- (5) Provide Ka band high speed data transmission link to Earth ground stations
- (6) Both S band and Ka band TT&C links are used
- (7) Minimum operational lifetime of 8 years
- (8) Provide short time relay communication services through lunar eclipse
- (9) Survive Earth eclipse at the Moon

An inclined highly elliptical frozen orbit was selected for the relay spacecraft, as shown in Figure 10. The orbit inclination is  $54.8^\circ$ . The minimum distance to the lunar surface is

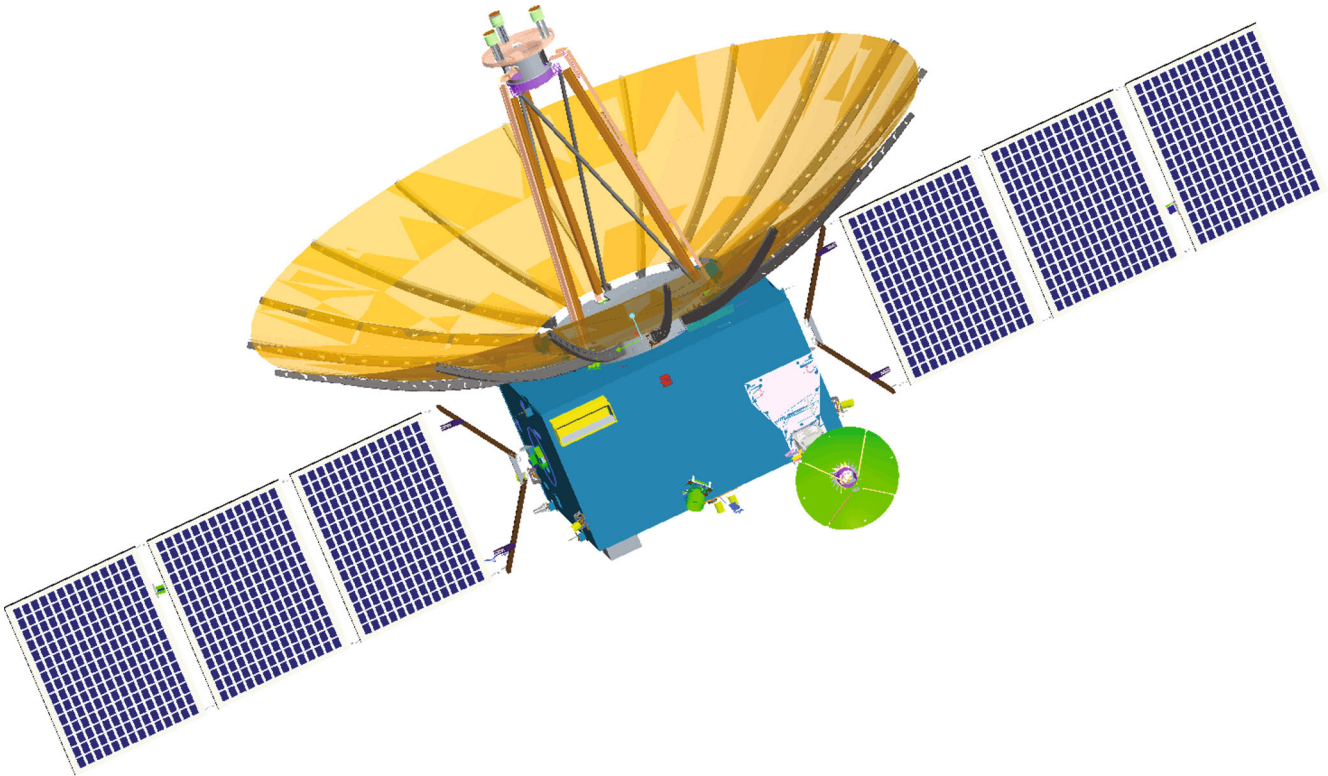


FIGURE 11: On-orbit configuration of relay satellite for lunar south pole mission.

300 km, and the maximum distance is about 8600 km. It enables a communication link to be established from the spacecraft to any surface element on the lunar south pole areas for over 8 hours, about two thirds of the orbit. If 100% coverage time is needed, a second relay spacecraft can be developed, and in the meantime, the robustness and redundancy of spacecraft can be enhanced.

The basic performance characteristics of the spacecraft include a wet mass of about 600 kg and about 1000 W orbit average power. If the spacecraft was launched by a dedicated launch vehicle, it would begin a translunar injection after separation from the launch vehicle. The total delta-V requirement for inserting to the frozen mission orbit with a 12 hours period is approximately 600 m/s. If it is launched together with other probes and separated from the polar orbit around the Moon, the total delta-V requirement for inserting to the mission orbit is about 350 m/s. It will be provided by a hydrazine propulsion system, inherited from Queqiao relay satellite for Chang'e-4 mission.

The relay satellite is a three-axis stabilized platform inherited from Queqiao. Six S band omnidirectional antennas and two USB transponders are used for USB TT&C link of the satellite. In addition, Ka band TT&C link can be provided. The power supply system uses triple-junction GaAs solar arrays (1000 W output power at EOL) and a 90 Ah Li ion storage battery. The attitude of the satellite is maintained with four reaction wheels and determined with a combination of three star trackers, two inertial measurement units, and digital sun sensors. The on-orbit configuration of the satellite is shown in Figure 11.

The spacecraft would operate in this orbit for a nominal 8-year mission life. Because the orbit is very stable, different from Queqiao, the satellite does not need to carry more propellant for orbit maintenance.

Unlike Queqiao which uses only the transparent relay mode, for this new relay satellite, both the transparent relay mode and regenerative relay mode can be provided. This enhances the relay flexibility for different users. X band will be the first choice for the relay communication links between the relay satellite and the spacecraft on the lunar surface, which will be compatible with existing technical status. A body-fixed umbrella-like parabolic antenna with 4.2 m aperture, already used by Queqiao, is used for the relay communication links with spacecraft on the lunar surface. Ten relay communication links for both forward relay communication and backward communication can be provided simultaneously. The satellite allows return data rates of about 50 kbits/s for a lunar surface user with an omnidirectional antenna. If the user carries a directional antenna with high gain, the return data rate can be increased to more than 10 Mbits/s. For the forward link, if an omnidirectional antenna is used, the data rate is 1 kbits/s for each user. If a directional antenna is used, data rates of over 1 Mbits/s can be achieved.

The relay satellite will transmit its own data as well as the science and exploration data gathered by surface assets in the lunar south pole areas, back to ground stations on Earth. Ka band will be used for the data transmission link. A two-axis gimbaled Ka band parabolic antenna with 0.6 m diameter will be used for this link. By means of QPSK modulation and low-



density parity-check (LDPC) coding, using a 55 W high efficiency K band traveling-wave tube amplifier (TWTA), the data rate is more than 100 Mbits/s. In addition, an S band low data rate link to the ground stations could be provided for the users that have no Ka band data receiving capability and can be used as a backup for the Ka band link.

As a new capability, the four-way ranging technique will be used to provide high precision location information for the lunar orbit spacecraft and lunar surface elements.

Operational flexibility and expandability are two important features for this relay satellite; so, apart from supporting Chinese lunar south pole exploration missions, it is anticipated to be used by other lunar missions, both domestic and international.

## 7. Prospect of the Lunar Relay Communication Satellite System Development

In the future, the sustainable human presence at the moon will be realized by means of a series of robotic and human exploration missions. More spacecraft will be sent to the Moon by more countries as well as commercial entities. These spacecraft will produce a large amount of data from different lunar locations including those with limited or no line of sight to Earth. For the future long duration robotic and human lunar missions operating on the lunar surface invisible from the Earth, the relay communication satellites will be needed in different orbits to support surface-to-surface and surface-to-Earth communications.

In order to deal with more lunar spacecraft and much larger volumes of data obtained from lunar missions, the future lunar relay communication infrastructure will be developed based on extending terrestrial telecommunications, navigation, and networking technical capabilities. This information infrastructure should have the following key features [11]:

- (1) Creation of a lunar information network including orbiting and surface elements similar to the combination of orbiting relay satellite systems and ground networks for the Earth
- (2) Use of higher frequency RF bands, especially Ka band, for higher forward and return relay communication data rates
- (3) Use of new optical communication technologies for extremely high data rates
- (4) Introduction of a solar system internet, operating like terrestrial internet, to provide network layer services to users
- (5) Establishment of an open, interoperable architecture to enable any number of national, international, and commercial service providers to offer services
- (6) Introduction of real-time service requests and network roaming among service providers rather than the single network, highly scheduled operations of the past

- (7) Use of automation and autonomous operations to reduce costs, enhance operational flexibility, and enable sustainable network evolution

Apart from relay communications, navigation is another important requirement for lunar exploration missions [12]. Navigation information should be available at all times which allow greater mobility on the lunar surface and provide better position knowledge as well as high precision clock information for more ambitious operations, especially for the manned lunar missions. So, the future lunar relay communication system and navigation system should be developed together. A complete lunar information infrastructure should provide global, continuous high precision navigation information and full communication connectivity among lunar surface elements and the Earth. It can offer flexibility to support evolving user requirements and meet the final objectives of sustainable lunar explorations.

The hybrid constellation with multiple spacecrafts, operated in different orbit planes around the moon and the orbits around the Earth-Moon libration points, can provide greater geometric diversity, which is favorable for improving navigation performance. Multiple relay spacecrafts also provide 100% communication and navigation availability for any position on the lunar surface and lunar orbit and even the whole *cis*-lunar space. In the meantime, the robustness of the service can be improved greatly.

For the future lunar relay communication system, the on-board routing among communication elements should be handled flexibly. Delay tolerant networking (DTN) and crosslink capability among multiple relay satellites is necessary to provide communications to invisible nodes (on the far side or in craters on the south pole) on the Moon. With the number of such nodes increasing, the system can adapt automatically to network dynamics and enable the lunar communication network to function well in a dynamic space environment. The future relay spacecraft should have the capability to autonomously discover the neighbor spacecraft and surface assets, establish variable-rate links, and communicate simultaneously with multiple users in the lunar space and lunar surface at varying and rapidly changing distances while making optimum use of the available onboard resources.

In the long run, the lunar information infrastructure with communication and navigation elements located both in the lunar orbit and lunar surface would provide the required capability to multiple users of multiple missions. Apart from the support from orbit elements, communication towers and base stations on the lunar surface can enhance communication link capabilities to the rover-like moving systems on the lunar surface and not be limited to direct line-of-sight to Earth communications. The future lunar information infrastructure should be compatible with terrestrial communication and navigation infrastructure to enhance support capabilities as well as reduce system risk and cost. In the future, commercial information support services covering communication and navigation capabilities are likely to be provided for lunar exploration missions.

The extension of human presence into the *cis*-lunar space is important trend in future human and science explorations.

Communication interoperability capabilities can benefit lunar exploration missions by reducing communication costs and expanding capability beyond a single mission and single nation approach [13]. More international collaboration opportunities can be anticipated in future lunar missions. A sustainable communication and navigation infrastructure should be established to benefit all lunar missions rather than dealing with each mission independently. This infrastructure should adopt open and extensible architecture and provide flexible, interoperable, cross-supportable, and compatible communications services, which is critical to the success of future robotic and human lunar explorations.

## Conflicts of Interest

The author declare that there are no conflicts of interest regarding the publication of this article.

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