Introduction to the TT&C Scheme for Chang'e-5 Mission

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Abstract: Chang'e-5 mission is China's first lunar sample return mission. It contains several new flight phases compared with the previous lunar missions, such as the lunar take-off and orbit insertion phase, the rendezvous and docking phase, etc. Chang'e-5 mission is extremely complicated and full of new challenges. This paper sorts out the characteristics and the difficulties in telemetry, tracking, and command (TT&C) of Chang'e-5 mission. The main technical contribution is a reliable general design of the TT&C system, including the application of X-band TT&C in launch and early orbit phase (LEOP), multiple targets simultaneous TT&C in X-band, lunar surface benchmark calibration, high-precision and rapid orbit trajectory determination for the lunar surface take-off, remote guidance rendezvous and docking, the determination of the initial navigational value for the separation point of the Chang'e-5 orbiter and returner, and the design of the reentry measurement chain. Based on this scheme, a global deep space TT&C network and interplanetary reentry measurement chain have been established for China, and near-continuous TT&C support for China's first extraterrestrial object sampling and return mission has been realized, ensuring reliable tracking, accurate measurement and accurate control. The global deep space network can provide TT&C support comparable to that of National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) for subsequent lunar and deep space exploration missions. The techniques of rapid trajectory determination of lunar take-off and orbit entry, as well as high precision and remote guidance of lunar orbit rendezvous and docking can lay a technological foundation for the future manned lunar exploration missions and planetary sampling and return missions.

Key words: Chang'e-5; telemetry, tracking and command (TT&C); the third phase of China lunar exploration program; lunar exploration; system design

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0 Introduction

China's first lunar explorer, Chang'e-1, was launched in 2007 and circled the moon for more than one year. China's first lunar lander, Chang'e-3, was launched in 2013 and successfully released a rover on the lunar surface. Chang'e-5 mission is the third phase of the China lunar exploration program, the final step of the three-stage "circling, landing and returning" of the China lunar exploration program[1]. Chang'e-5 explorer was launched in Wenchang launch site with the Long March-5 carrier rocket on 24 November, 2020 (Beijing time). And 23 days later, on 17 December, 2020, it carried the lunar samples back to the earth, and fullfilled the first sample return mission of extraterrestrial celestial bodies in China. Chang'e-5 mission contains several new flight phases compared with the previous lunar missions, such as the lunar take-off and orbit insertion phase, the rendezvous and docking phase, etc. These make the mission extremely complicated and full of new challenges. It is "the aerospace system engineering with the highest complexity and the largest technical span" [2] in China.

During the implementation of the mission, the telemetry, tracking, and command (TT&C) system is mainly responsible for TT&C of the Long March-5 rocket, orbit determination, state monitor-

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ing and flight control of the Chang'e-5 explorer in each flight phase, lunar surface positioning and sampling operation control of the explorer after landing on the Moon, and the reentry measurement of the returner. Through the cooperation of the space segment and the ground segment, reliable tracking, accurate measurement and accurate control are realized.

This paper sorts out the characteristics and difficulties in TT&C of Chang'e-5 mission, conducts a comprehensive analysis and systematic solutions for the key problems, and summarizes the implementation effect of the mission. The practice of the mission shows that the design of the TT&C system is stable and reliable, and can effectively ensure the complete success of the mission, and provide reference for the TT&C scheme design of China's subsequent lunar and deep space exploration missions and manned lunar exploration missions.

1 Overview of Chang'e-5 Mission

1.1 Chang'e-5 explorer

The Chang'e-5 explorer has a total mass of about 8 200 kg and is composed of four parts: An orbiter, an ascender, a lander and a returner. The overall configuration is shown in Fig.1[3].

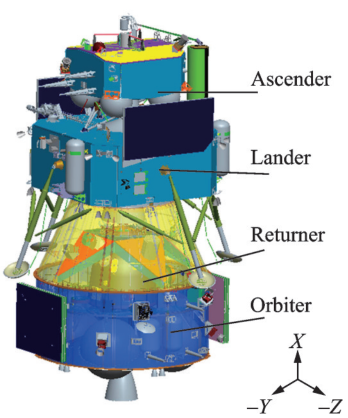

Fig.1 Overall configuration and coordinate system of Chang'e-5 explorer

The TT&C subsystem of the orbiter's ground monitoring and control adopts the unified X-band (UXB) TT&C scheme. There are two groups of frequencies of the orbiter. Each group includes an uplink frequency and a downlink frequency, and the turnaround ratio is 880/749. The high-speed data transmission from the orbiter to the ground adopts X-band suppressed carrier TT&C scheme with only one downlink frequency. The TT&C subsystem of the ascender also adopts UXB TT&C scheme. There are two groups of frequencies of the ascender. Each group includes an uplink frequency and a downlink frequency, and the turnaround ratio is 880/749. The high-speed data transmission from the lander to the ground adopts X-band suppressed carrier TT&C scheme with only one downlink frequency. The TT&C subsystem of the returner adopts the unified S-band (USB) TT&C scheme, with only one group of frequency and the turnaround ratio is 240/221.

1.2 Flight process of the mission

The Chang'e-5 explorer was launched by Long March-5 rocket to an Earth-Moon transfer orbit with a perigee of 200 km and an apogee of 380 000 km. After separating from the rocket, the explorer, with the support of ground TT&C, carried out mid-course correction, implemented orbit insertion at the near-Moon point, and entered the orbit around the Moon. During the circumlunar phase, the lander-ascender and the orbiter-returner were separated. The orbiter-returner continued in orbit around the Moon, while the lander-ascender made a soft landing in the predetermined area on the lunar surface after two orbital maneuvers and dynamic descent flight. After landing, lunar surface samples were collected and encapsulated during the lunar surface operation phase. During the circumlunar flight and the lunar surface operation phase, the orbiter-returner completed four orbit maneuvers for phase adjustment and orbit change. Then the ascender took off from the lunar surface and entered the rendezvous and docking orbit. After the rendezvous and docking with the ascender, the lunar samples were transferred from the ascender to the returner, and then the ascender was separated from the orbiter-returner. At a predetermined time, the orbiter-returner entered the Moon-Earth transfer orbit, and at an altitude of about 5 000 km from the earth, the returner and the orbiter were separated and reentered the atmosphere, and finally returned to the landing site in

Siziwang Banner, Inner Mongolia.

The schematic diagram of the whole mission flight process and the reentry phase are shown in Figs.2,3.

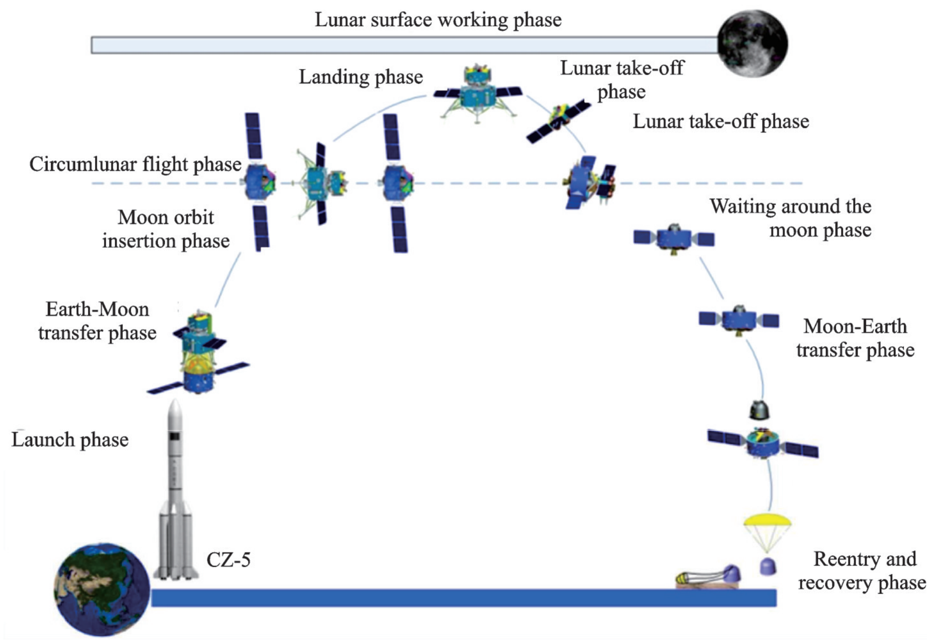

Fig.2 Schematic diagram of the whole mission flight process

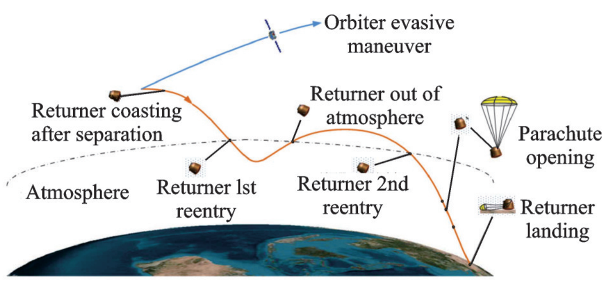

Fig.3 Schematic diagram of the reentry section

2 Difficulties and Challenges of TT&C System

Compared with the previous Chang'e missions (from Chang'e-1 to Chang'e-4), The TT&C system of Chang'e-5 mission faces many new challenges. These challenges can be divided into three categories: The requirements of the new X-band TT&C for launch and early orbit phase (LEOP), the requirements of the new multi-target TT&C and its coverage, and the new requirements brought by the new mission phases.

2.1 Requirements of the new X-band TT&C for LEOP

The previous Chang'e missions used S-band TT&C for LEOP. In order to optimize the weight of the explorer, Chang'e-5 mission adopts X-band TT&C scheme. The TT&C system needs to be able to support X-band TT&C in the launch phase and meet the mission requirements of the explorer system to quickly capture and issue commands.

2.2 New requirements of the multi-target TT&C and its coverage

In the previous Chang'e missions, there was only one TT&C target before landing on the Moon. However, Chang'e-5 mission needs to carry out reliable X-band TT&C for at most three targets and six frequencies at the same time in the lunar orbit. This needs the TT&C system to simultaneously handle TT&C of multiple targets and multiple frequencies (Fig.4) and meet the requirements of high-precision orbit determination. The previous Chang'e-5 mission required a TT&C coverage rate of up to 60%. This can be achieved by China's two deep space stations in Jiamusi and Kashi. However, since Chang'e-5 mission is required to complete the key tasks such as lunar surface sampling, rendezvous and docking, the TT&C coverage requirement is 90%. It is necessary to build a TT&C network that meets the coverage requirements.

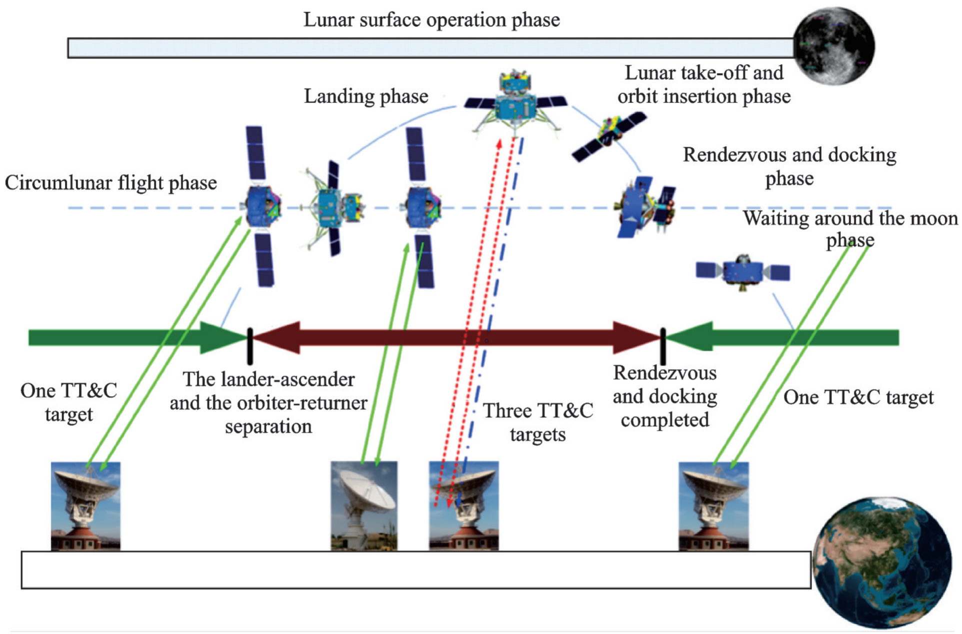

Fig.4 Diagram of multi-target TT&C requirement in X-band

2.3 New requirements of the new mission phases

Compared with the previous missions, Chang'e-5 mission has added new flight phases such as lunar take-off and orbit insertion phase, rendezvous and docking phase, waiting around the moon phase, Moon-Earth transfer phase and reentry phase. In order to realize the accurate orbit insertion of ascender, it is necessary to study the high-precision calibration technology of lunar take-off datum. In order to ensure the successful completion of lunar orbit rendezvous and docking, it is necessary to study the multi-target high-precision remote guidance method. In order to ensure the accuracy of the initial navigational value of the returner, it is necessary to ensure that the accuracy of the orbit determination before the separation of the orbiter and the returner meets the interface requirements. In order to ensure the reliable capture and tracking the returner of the reentry process, it is necessary to support the construction of the USB TT&C equipments and radar equipments with a larger scanning range.

3 Scheme Design of TT&C System

In Chang'e-5 mission, the TT&C system includes launch phase TT&C chain, ground based TT&C network, very long baseline interferometry (VLBI) observation network and reentry measurement chain. In regard of the aforementioned difficulties, the TT&C system has bean carried out the design demonstration, problems in key technologies, and the scheme design.

3.1 X-band TT&C in LEOP

For the X-band TT&C in the launch phase, two sets of UXB equipment were mounted on two TT&C ships to support TT&C in the launch phase of Chang'e-5 mission and ensure the transmission of key commands before the explorer-rocket separation. Given the narrow beam of X-band, the X-band equipment of the TT&C ships is equipped with 1.8 m aperture guiding antenna with a beam range of 1.4° to realize the fast acquisition and tracking of the downlink signal of the explorer.

In order to ensure the TT&C coverage and the command requirements of the launch phase, it is considered to deploy the TT&C ships in the waters east of Philippines and the waters of French Polynesia. The X-band doppler frequency in the tracking passes of the TT&C ship have a range of 500 kHz and a variation rate of 7 kHz/s, and the doppler frequency range was 135 kHz in the previous missions in S-band and a variation rate of 1.9 kHz/s. For the large dynamic signal capture, a two-way acquisition strategy is designed with preset the Doppler frequency, the increased frequency-sweeping rate (from

15 kHz/s to 28 kHz/s) and the reduced frequency-sweeping range (from 460 kHz to 300 kHz)[4]. This strategy can greatly reduce the two-way acquisition time and ensure that the TT&C ships could complete the system acquisition and start sending the command within 60 s.

Based on the nominal trajectory, the Argentina deep space station begins to track the Chang'e-5 explorer 6 min (10° elevation) after the separation of the explorer and the rocket. The TT&C system needs to capture downlink signals quickly and reliably in order to judge the working condition of the explorer. The antenna diameter of the Argentina deep space station is 35 m, and its beam range of X-band is only 0.07°. If the launch vehicle has a large deviation in orbit, the position of the explorer will greatly exceed the beam range of the station, so there is a risk that the signal of the explorer cannot be captured.

In order to ensure the ground TT&C station can quickly and reliably capture the signal of the explorer and monitor the working conditions of it, the European Space Agency (ESA) Kourou station is used as a backup of the 35 m antenna in the Argentina deep space station. The Kourou station is located in French Guiana, South America, and its 15 m X-band TT&C equipment has wide beam guiding capability of X-band (equipped with a 1.3 m aperture guiding antenna). The beam of the 35 m antenna in Argentina deep space station is only 1/27 of that of the 1.3 m guide antenna of the Kourou Station. The Kourou station is used as a backup, which reduces the acquisition risk and enhances the mission reliability.

In order to verify the interface compatibility between the Chang'e-5 orbiter and the TT&C station affiliated to ESA, China and ESA conducted the TT&C compatibility test at the European Space Operations Center (ESOC) in 2017, and conducted a full-loop ground to ground interface test between the Chang'e-5 orbiter to Beijing Aerospace Control Center (BACC) via ESOC[5]. It ensures that the ground to ground interface is matched, and the relevant technical characteristics can meet the requirements of Chang'e-5 mission.

3.2 Multi-target simultaneous X-band TT&C

There is only 48 h for drilling sampling, surface sampling, and payload detection in the lunar surface operation phase, which requires a continuous TT&C support. In addition, from the separation of the lander-ascender and the orbiter-returner to the completion of rendezvous and docking, it is necessary to track multiple targets and multiple frequencies at the same time, i.e. supporting at most three targets and six frequencies at the same time. Before the orbiter-returner separation, it is necessary to meet the TT&C requirements of the orbiter in X-band and give consideration to the TT&C of the returner. However, the coverage rate of TT&C in the lunar surface operation phase of Jiamusi and Kashi deep space stations is only 60%, which is not enough for drilling and surface sampling at full term. The two 18 m-antenna stations of Qingdao and Kashi cannot meet the TT&C requirements of the orbiter-returner. In addition, the existing TT&C resources connot meet the requirements of the X-band TT&C and data transmission of the orbiter and the S-band TT&C of the returner at the same time before the orbiter-returner separation.

In response to the need for continuous TT&C support in the whole lunar surface operation phase, the Argentina 35 m-antenna deep space TT&C station was built in 2017, and is able to work simultaneously at S/X/Ka frequency bands, in which S/X can work in the uplink and downlink, and Ka band can work in the downlink. The performance indicators have reached the international advanced level. In order to meet the TT&C requirements of X-band before and after the separation point of the orbiter and at the same time take into account the TT&C of the returner, Namibia 18 m S/X dual-band TT&C equipment was built. The equipment was completed in 2016 to guarantee the simultaneous TT&C of the orbiter and returner before the orbiter-returner separation and also used for the TT&C coverage of the important tracking pass[6].

Through the supplementary construction described above, a pattern of "three networks plus" has been formed, namely "deep space TT&C network, 18 m-antenna TT&C subnetwork and VLBI observation network" plus "TT&C equipment of TT&C ships, TT&C equipment of Sanya station, and TT&C equipments of ESA". The layout of Chang'e-5 mission TT&C network is shown in Fig.5.

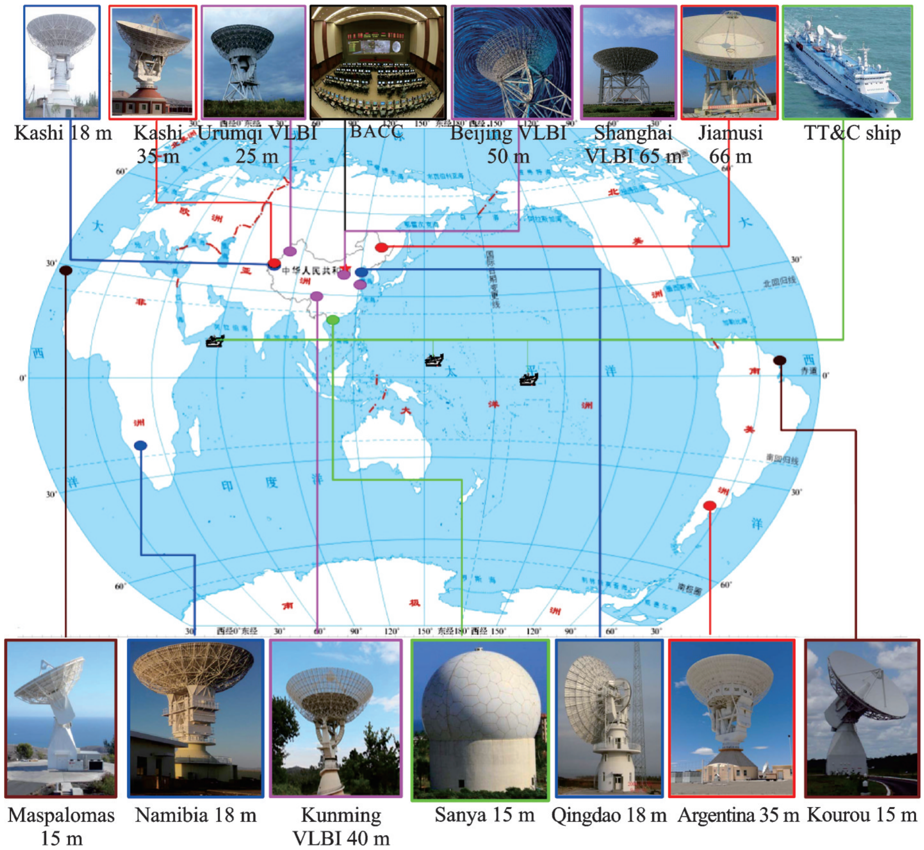

Fig.5 Layout of the TT&C network for Chang'e-5 mission

3.3 Calibration of lunar surface datum and rapid determination of take-off trajectory

The high precision calibration technology of lunar take-off datum is the prerequisite for the accurate orbit entry of ascender and the successful rendezvous and docking. This is because, according to the mission flight procedures, before rendezvous and docking, the orbiter has been operating in the lunar orbit for a long time, so it can accurately determine the orbit prediction. After the ascender takes off from the Moon and enters the orbit, it completes four orbit changes according to the rendezvous and docking strategy, and finally enters the short-range guidance phase implemented independently when the ascender is 50 km in front of and 10 km above the orbiter. Due to the limited weight of the ascender, the small amount of fuel is carried, so the orbit change capability is limited. It is required that the accuracy of lunar launch into the orbit must be accurate, so as to reduce the unnecessary orbit change consumption.

In order to calibrate the lunar take-off datum with high precision and quickly determine the trajectory of the take-off, a measurement method using "three-way measurement system[7] + VLBI interferometry system" is designed. The domestic big triangle composing of Jiamusi deep space station, Kashi deep space station and Sanya station provides the strongest geometric constraint for the ascender within China's territory. The accuracy of the three-way ranging is 5 m, The accuracy of three-way doppler is 1 mm/s. Meanwhile, VLBI is carried out at Beijing, Shanghai, Kunming and Urumqi stations of China's VLBI network, breaking through the quasi-real-time fast frequency synthesis technology of VLBI multi-channel data, and shortening the lag time of VLBI measurement data from 5 min to 25 s[8].

Based on this scheme, accurate measurement of the lunar take-off datum and real-time monitoring of the trajectory of the ascender's lunar take-off process can be realized, thereby providing an important criterion for judging if the ascender entries into the predetermined orbit.

3.4 High precision remote guidance in the rendezvous and docking phase

The Lunar orbit rendezvous and docking of the Chang'e-5 mission adopts the orbiter-returner actively docking with the ascender as the target, and the orbiter-returner is the tracker. The TT&C system will guide the two targets from thousands of kilometers to the transition point of 50 km. At the time, the ascender is in a circular orbit with the height of 210 km and coplanar with the orbiter-returner. The ascender is 50 km in front of and 10 km above the orbiter. The orbit determination prediction accuracy of the two targets should meet the requirements of turning into autonomous guidance control procedure.

The TT&C system only relies on the limited resources of ground-based orbit measurement to realize the remote guidance of rendezvous and docking, which faces two challenges.

(1) Short tracking pass of orbit measurement. According to the design of the rendezvous and docking remote guidance strategy, the ascender will complete four orbit changes, including phase adjustment maneuver, orbit plane modification, altitude adjustment of the apolune and circular maneuver, within 48 h after taking off from the lunar surface and entering the orbit. Between two orbit changes, the tracking passes can be used for orbital determination are at least one and at most three.

(2) High accuracy requirement for remote guidance. The semi-major axis error is 30 m; the eccentricity error is 0.000 03; and the orbital plane pointing error is 0.01°.

Therefore, the TT&C system fully optimizes the allocation of existing ground TT&C resources, and designed a comprehensive orbit measurement scheme based on "ranging and doppler measurement +VLBI + same beam interferometry (SBI)". The ascender is tracked and measured by Kashi, Jiamusi, and Argentina deep space stations and four domestic VLBI stations[9]. The Kashi, Qingdao, and Namibia 18 m aperture stations are used to track and measure the orbit of the orbiter, to achieve the 1 m ranging accuracy as well as the 1 mm/s doppler accuracy. Through the technical breakthrough, the high-precision SBI technique for two fast moving targets is realized. When the distance between two targets is within 1 000 km, the relative position can be measured by SBI at four VLBI stations in China. The schematic diagram of SBI measurement is shown in Fig.6.

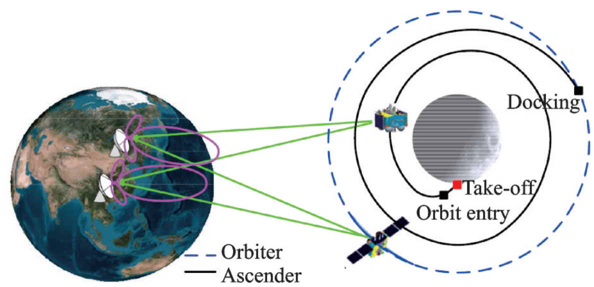

Fig.6 Schematic diagram of SBI measurement

3.5 Determination of initial navigation value of orbiter-returner separation point

Before the orbiter-returner separation, the nadir point of the orbiter-returner is located near 30° south latitude (Fig.7), instead of in the domestic TT&C area. The TT&C stations that can be used include Namibia station built in Walvis Bay, Namibia and the Argentina deep space stations built in Neuquen, Argentina. The last mid-course correction (the sixth mid-course correction) of the orbiter-returner only takes about 4.5 h before orbiter-returner separation, which requires 1 h orbital determination prediction to the separation point by the TT&C system. The position accuracies of three directions (RTN, radial, tangential and normal) are better than 1 000 m (3σ), and the velocity accuracies are better than 0.5 m/s (3σ). However, the actual measurement data that can be used for orbital determination is only 3 h. Through the simulation analysis of orbit measurement and determination, no matter what orbit measurement strategy is adopted in Na-

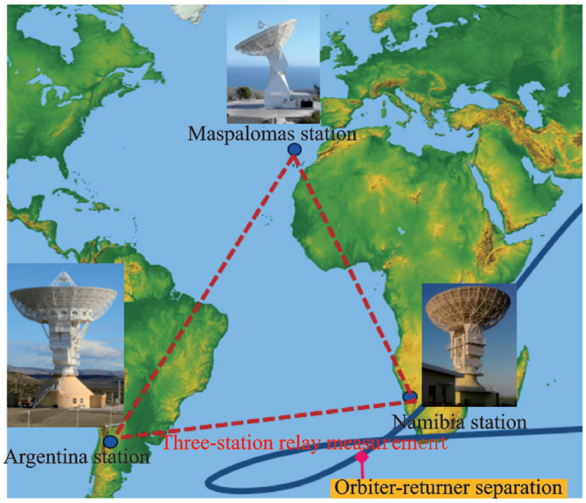

Fig.7 Schematic diagram of three-station relay measurement

mibia station and Argentina deep space station, it cannot meet the mission requirements. Therefore, the TT&C system proposes the strategy of using ESA's Maspalomas station, and adopts the three-station three-way measurement, including three-way ranging and three-way doppler, to improve the accuracy of orbit determination prediction[10]. Located near 30° N, Maspalomas station along with Namibia station and Argentina deep space station, form a "grand triangle", effectively improving the measurement geometry. The three-way measurement mode has been successfully applied in the lunar landing process of Chang'e-3 mission[11], and the data accuracy is significantly better than the single-station two-way ranging and doppler measurement. Unfortunately, through coordination with ESA, the Maspalomas station is not able to conduct three-way ranging. In view of this situation, a strategy of three-station relay measurement is proposed for the TT&C system, i.e. Argentina deep space station, Maspalomas station and Namibia station carry out two-way ranging and Doppler measurement individually. By evenly distributing available tracking pass resources to the above three stations, the measurement geometry can be effectively improved to meet the accuracy requirements of orbit determination prediction[12-13].

3.6 Design of reentry measurement chain

The returner is small in size and radar cross section (RCS), and it returns by semi-ballistic jump reentry with a high reentry velocity and a large ballistic dispersion. In order to ensure reliable tracking and a measurement of the reentry process, supplementary construction of TT&C system is carried out, and a lunar reentry measurement chain (Fig.8) consisting of "radar equipment + TT&C equipment + optical equipment" is constructed.

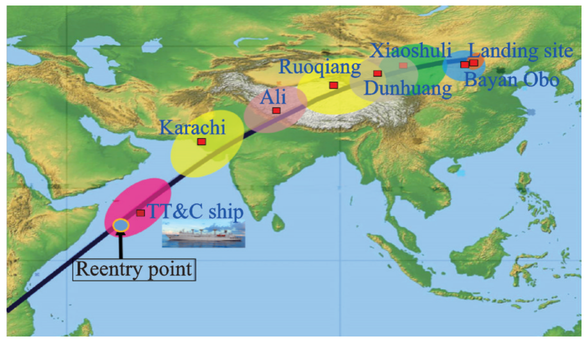

Fig.8 Reentry measurement chain

The first reentry height of the returner is 120 km, and then the height decreases quickly. The lowest point is about 55 km, and then the altitude increases gradually to the peak. After that the height is again reduced to reentry the atmosphere for the second time.

When the lowest point of the first reentry is reached, the jump height is a key parameter of the process. If the jump height is too high, the returner will fly out of the atmosphere; while if the jump height is too low, the returner will fly directly into the Indian Ocean. The TT&C system needs to ensure that the returner has a reliable measurement before and after the lowest point of reentry, and determines the jump height reliably.

The whole flight process of the first reentry of the returner is located over the Indian Ocean without land-based TT&C stations. The TT&C system solves the limitation of resources without land-based TT&C stations by setting a TT&C ship in the waters east of Somalia[14]. Before entering the black barrier, the TT&C equipment of the ship starts to receive telemetry steadily, providing guidance for radar equipment and optical equipment. After entering the black barrier, reflection tracking by radar equipment and camera shooting by optical equipment are carried out.

Given the large range of ballistic dispersion of the returner after it is out of the first black barrier, the Karachi wide beam guiding equipment and the vehicle-mounted multi-beam equipment located in Ali, Tibet are responsible for the capture and tracking of the returner. The capture range of the Karachi wide beam guiding equipment reaches 18° and that of the vehicle-mounted multi-beam equipment reaches 20°, both of which can cover the dispersion range of the returner under normal ballistic deviation. Subsequently, the radars deployed in Xinjiang, Qinghai, Inner Mongolia and other places carry out continuous measurement of the returner before the second entry into the black barrier until the parachute of the returner open, to ensure reliable tracking of the returner. A mobile optical recording equipment is set up in the landing area to record the process of the returner's parachute open and landing.

4 Mission Implementation Effects

In the mission implementation process, the TT&C system successfully completes the work undertaken according to the established plan. Mission practice shows that the TT&C system scheme is reliable and effective, which ensures the complete success of Chang'e-5 mission.

During LEOP, the Yuanwang-6 ship was located in the sea east of the Philippines, which realized the tracking pass lap with the mainland TT&C station, ensuring the TT&C coverage during the whole process from the rocket take-off to the first shutdown of the second stage. The Yuanwang-5 ship was located near French Polynesia, which ensured the telemetry acquisition and command transmission before and after the separation of the explorer and the rocket. In the blank tracking pass between the two ships, space-based telemetry was received by relay satellites, so as to ensure the continuous acquisition of telemetry data of rockets in the whole launch section. In the actual misson, Yuanwang-6 ship only used 15 s to complete the two-way frequency acquisition. Both the Argentina deep space station and the ESA's Kuru station successfully captured the signals from the Chang'e-5 explorer after the separation.

The deep space TT&C network composed of Kashi, Jiamusi and Argentina deep space stations ensured the continuous TT&C during the 48 h lunar surface sampling phase, and the 18 m-antenna TT&C subnetwork composed of Kashi, Qingdao and Namibia stations successfully completed the TT&C work of the orbiter-returner. The difference between the lander's lunar surface positioning accuracy and the image data obtained by lunar reconnaissance orbiter (LRO) is only 60 m[15], which can be effectively used as the lunar surface liftoff datum mark. The initial orbit was determined by using the measurement data 30 minutes after the ascender was put into orbit.

In the rendezvous and docking phase, the semi-major axis accuracy of the ascender at the remote guided shift point was up to 10 m; the eccentricity accuracy was up to 1e−5, and the orbital plane pointing accuracy was up to 0.005°, which met the mission requirements of the ascender and orbiter-returner to transfer to short-range autonomous guidance control.

After the fifth midcourse orbital correction of the orbiter-returner, the TT&C system and explorer system jointly evaluated the correction effect, which met the conditions for canceling the sixth midcourse orbital correction. Therefore, the sixth midcourse orbital correction was not implemented, and the whole 16 h tracking data after the fifth midcourse orbital correction to orbiter-returner separation were used for the high-precision orbital determination. Under the circumstance, the accuracy of track prediction was satisfied without three-station relay measurement.

After the orbiter-returner separation, the returner entered the tracking pass of the Karachi wide beam guiding equipment before and after the first black barrier. The tracking state of the equipment was affected by the black barrier at the initial stage of acquisition. Subsequently, Ali vehicle-mounted multi-beam equipment completed the capture of the returner normally, obtained the telemetry data of the returner, and sent the command as planned.

Subsequent measurements were carried out by various radar and USB equipments to ensure the full coverage from the second reentry phase to the parachute-opening of the returner, and image data were successfully obtained by optical equipments.

5 Conclusions

The successful implementation of Chang'e-5 mission has brought a satisfactory end to the three stages of China lunar exploration program. In the design stage of the mission, the mission requirement analysis, the technical difficulty identification and the system scheme design are conducted according to the actual TT&C requirements of the lunar sampling return mission. The main technical problems are solved, including the X-band TT&C in LEOP, the multiple targets simultaneous TT&C in X-band, the lunar surface benchmark calibration, the high-precision and rapid orbit trajectory determination for the lunar surface take-off, the rendezvous and docking remote guidance, the determination of the initial navigational value for the separation point of the orbiter and returner, the design of the reentry measurement chain. A reliable general TT&C scheme has been designed. China's global deep space TT&C network and interplanetary reentry measurement chain have been established. Near-continuous TT&C support for China's first extraterrestrial object sampling and return mission has been realized, ensuring reliable tracking, accurate measurement and accurate control. The global deep space network can provide TT&C support comparable to that of National Aeronautics and Space Administration (NASA) and ESA for subsequent lunar and deep space exploration missions. The techniques of high-precision and rapid orbit trajectory determination for the take-off from lunar surface, as well as rendezvous and docking remote guidance can lay a technological foundation for manned lunar exploration missions and planetary sampling and return missions.

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嫦娥五号任务测控系统方案设计

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摘 要:嫦娥五号任务是中国首次月球采样返回任务。与之前实施的探月任务相比,此次任务包括了多个全新飞行阶段,如月面上升入轨段、交会对接段等,这些均让任务变得极其复杂并充满新挑战。本文梳理了嫦娥五号任务在测控方面的特点和难点,开展了可靠的测控系统总体方案设计,主要技术点包括发射及早期轨道段X频段测控、多目标X频段同时测控、月面基准标定及起飞入轨段轨迹快速测定、交会对接段高精度远程导引、轨道器与返回器分离点导航初值确定、再入返回测量链设计等。基于此设计方案,建立了中国自己的全球布站的深空测控网和行星际再入测量链,实现了中国首个地外天体采样返回任务的近连续测控保障,实现了可靠跟踪、精确测量和精确控制。全球布局的深空测控网可为后续月球与深空探测任务提供比肩欧美的测控支持。月面起飞入轨快速轨迹测定与环月轨道交会对接高精度远程导引技术可为载人月球探测任务、行星采样返回任务奠定技术基础。

关键词:嫦娥五号;测控;探月工程三期;月球探测;系统设计