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• **REVIEW** •
Cover Article

Technological breakthroughs and scientific progress of the Chang'e-4 mission

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Abstract Chang'e-4 is the first man-made probe that accomplished landing and roving on the far side of the Moon, which is viewed as a new milestone in the history of Lunar exploration. Beginning with a brief introduction to the progress of domestic and foreign Lunar exploration, this paper reviews the implementation process of the Chang'e-4 project, sorts out the technical breakthroughs achieved, summarizes the exploration achievements, and provides references for subsequent Lunar exploration.

Keywords Chang'e-4, Moon's far side, soft landing, Earth-Moon L2 point relay satellite, technological breakthrough, scientific achievement

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1 Introduction

As the nearest celestial body to the Earth, the Moon is the preferred target for deep space exploration by humankind. So far, about 118 Lunar exploration activities have already been carried out. While more than 20 probes have landed on the near side of the Moon, the others have either orbited or only made flybys [1]. The far side of the Moon is an unknown world that cannot be observed from the Earth. On that part of the Moon are the largest, deepest, and most ancient craters of the Moon. The far side of the Moon is an ideal place to make radio astronomical observations. This is because it is always outside the Earth's line of sight, and radio signals from the Earth are blocked there. These observations will not only contribute to the research on major scientific problems of the cosmic dark and dawn ages, but also to the study of the early history and evolution of the Moon and the solar system [2–5]. A number of countries are yet to make it close to the far side of the Moon owing to the great technological challenges in terms of communicating with the Earth, landing, and roaming on the complex landform.

Recently, the European Space Agency has put forward a Lunar South Pole exploration plan to establish a "Moon village" at the South Pole. Russia has formulated a Lunar South Pole exploration plan to establish a "Lunar base" at the South Pole through the implementation of four missions, namely the Luna-25, Luna-26, Luna-27, and Luna-28. As a consequence of failed landing of the Chandrayaan-2 at the South Pole in 2019, India plans to launch another landing attempt on the South Pole around 2021 using the Chandrayaan-3. The Return to Moon project was unveiled in 2017 by the United States. In

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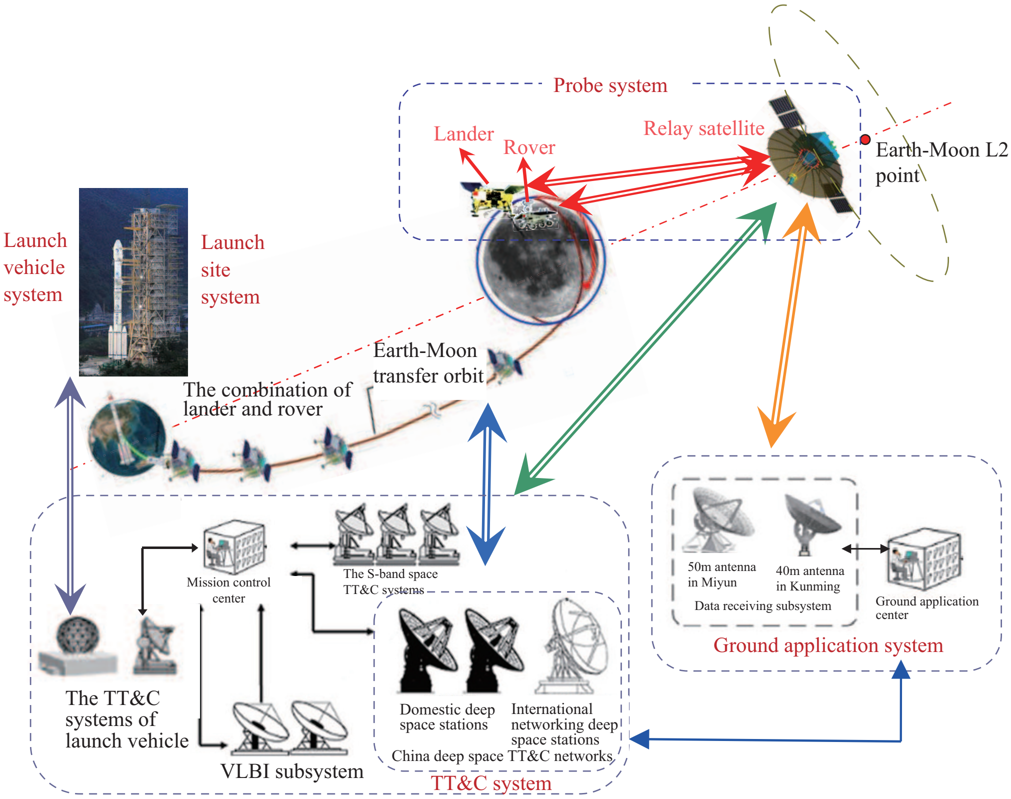

Figure 1 Composition of the Chang'e-4 project.

2019, the United States in its quest to lead humanity's endeavor in Lunar exploration, officially launched the Artemis program. The program is aimed towards making a manned landing on the South Pole of the Moon by 2024 [6–8]. It can be concluded that the South Pole of the Moon has become a strategic commanding height for which major space countries and organizations are racing to control.

China launched the Chang'e-4 project in 2014 and took the lead in carrying out the engineering work of landing on the far side of the Moon. In 2018 and 2019, for the first time in mankind's history, the Chang'e-4 project realized a relay communication based on the second Lagrangian Point of the Earth-Moon system. This was achieved by a soft landing in von Karman crater located at the South Pole's Aitken basin on the Moon's far side. Change'e-4's aim was to carry out experiments and scientific exploration. Hence, a new milestone in mankind's history of Lunar exploration was made possible. Since then, a series of breakthroughs of key technologies and a number of significant phased scientific achievements have been made.

2 Development history of the project

The Chang'e-4 project is comprised of top-level mission design segments and five affiliated engineering systems. These are the probe, launch vehicle, launch site, the TT&C and the ground application systems. They are as shown in Figure 1. The Chang'e-4 mission has 13 scientific instruments, shown in Figure 2, that include four international payloads from Germany, Sweden, The Netherlands, and Saudi Arabia. As part of the project, one piggyback microsatellite, which is a first of its kind, was developed and it orbited the Moon for astronomical observations. The Chang'e-4 project included two launches—one for the relay communication satellite and the other for the probe [9, 10].

In July 2014, the implementation plan was initiated. Through an in-depth demonstration and comparative study of multiple solutions, the implementation plan was later confirmed in May 2015. The plan was to develop a relay communication satellite that will orbit the second Lagrangian Point (L2) of the

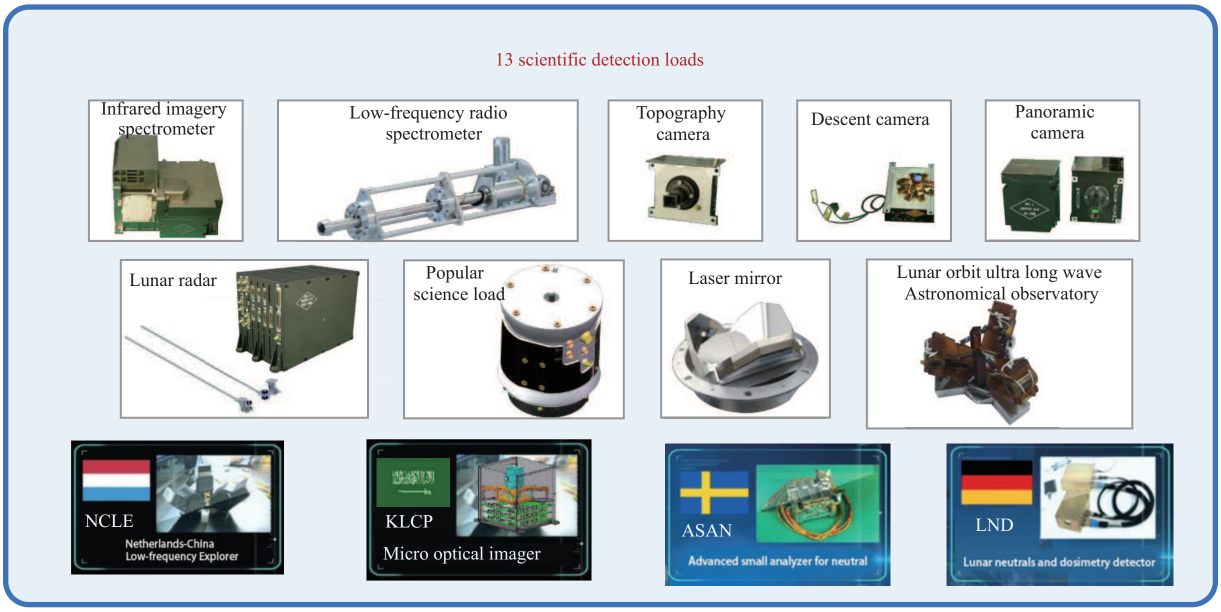

Figure 2 Scientific payloads of the Chang'e-4 project.

Earth-Moon system. This was made to develop a probe comprising of a lander and a rover that would land on the far side of the Moon and conducted *in situ* exploration activities. The rover was later named as Yutu-2. The project officially entered the implementation phase in January 2016.

The relay communication satellite, Queqiao, was launched into an Earth-Moon transfer trajectory by a Long March launch vehicle CZ-4C on the May 21st, 2018. By conducting several orbital maneuvers and captures, the satellite successfully entered the L2 point mission orbit. This is located at about 70000 km away from the Moon and 450000 km away from the Earth, achieved stable operation after 24 days [11]. The flight trajectory of the relay communication satellite is shown in Figure 3.

The probe was launched on the December 8th, 2018 by CZ-3B into an Earth-Moon transfer trajectory, the apogee of which was 420000 km. After mid-course corrections, a near Moon braking, Moon orbiting and an orbital descent, the probe started a powered descent at about 15 km from the surface of the Moon. After a 687-second process, including the main deceleration, quick-adjustment, approach, hovering, obstacle dodging and a slow descent, the probe safely landed on the pre-selected landing zone. This occurred at about 10:26 on the January 3, 2019 inside the von Karman crater on the far side of the Moon. The probe completed the separation of the lander and the rover with the two taking pictures of each other. With the support of the relay communication satellite, the probe started the long-term scientific exploration and experimentation as reported [10,12]. The flight trajectory of the probe is shown in Figure 4.

3 Major technological breakthroughs of the project

The Chang'e-4 project is a highly innovative and sophisticated project with high technical difficulty and significant international influence. The project has achieved a number of technological breakthroughs since its implementation is classified as follows.

3.1 World's first realization of continuous and reliable relay communication between the far side of the Moon and the Earth

A deep space relay communication scheme based on the regeneration and retransmission of the signals at the Earth-Moon L2 orbit was proposed. The relay communication link is shown in Figure 5. Key technologies, such as rapid scanning and acquisition of weak remote and demodulation signals with

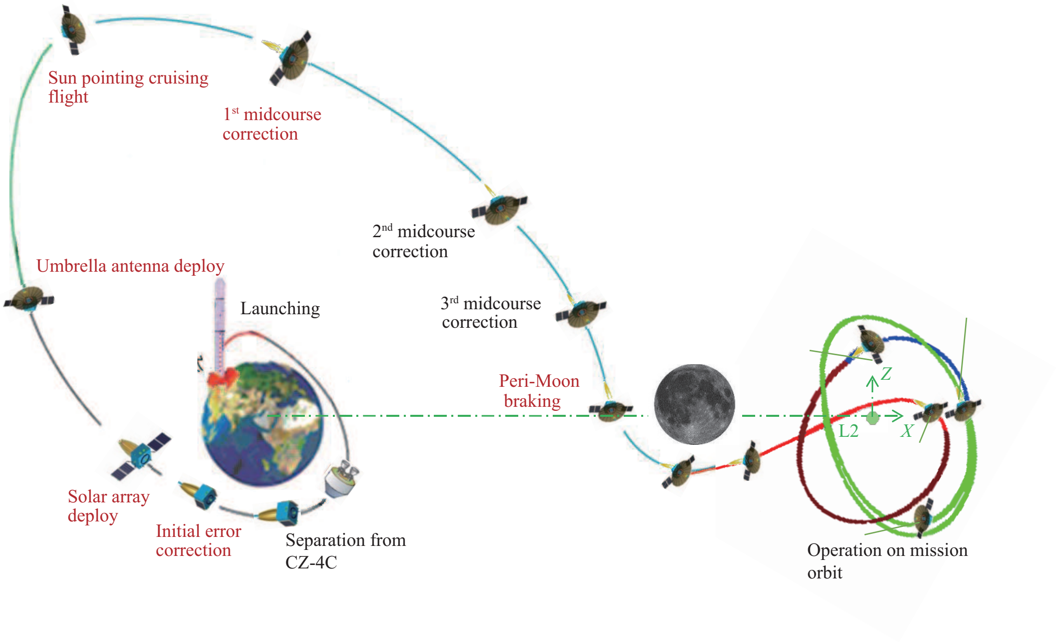

Figure 3 The relay satellite's flight trajectory.

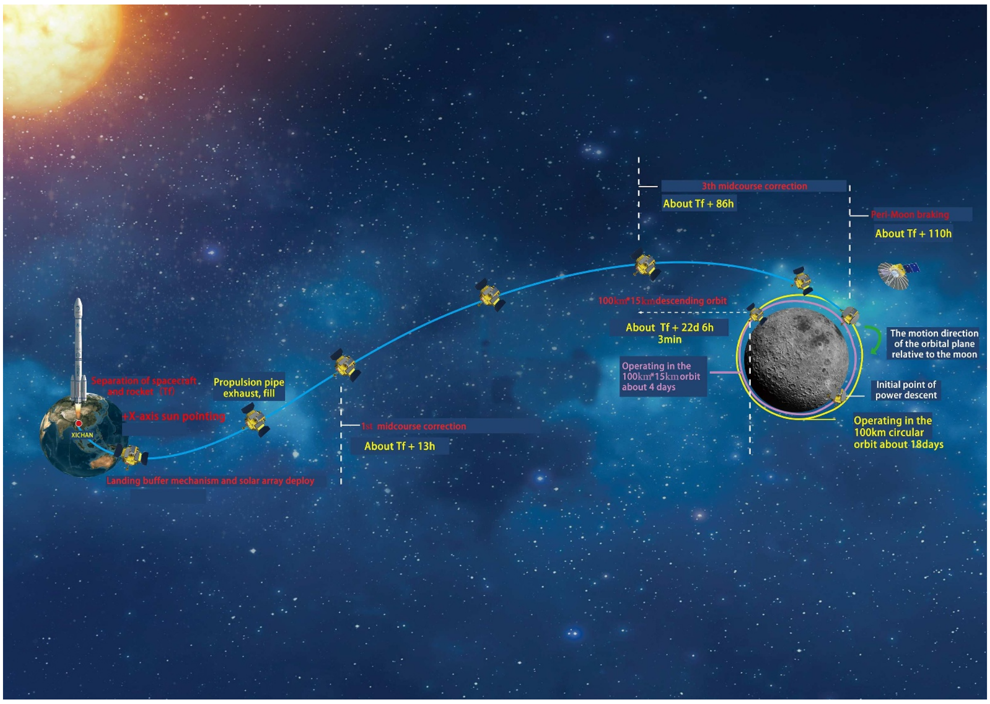

Figure 4 The probe's flight trajectory.

performance near enough to the theoretical limit were broken through. The reliable relay of broadband signals with low SNR has been realized, and the relay communication distance has thus increased from 40000 km to 450000 km [13].

A Halo mission orbit surrounding the Earth-Moon L2 point and a three-pulse orbit capture method were designed, the Earth-Moon Halo orbit configuration is shown in Figure 6. Key technologies, such as the orbit design and control under the condition of multi-constraints coupling have also had breakthrough. The difficulty of stable relay communication between the communication satellite and the probe on the far side of the Moon was solved [14].

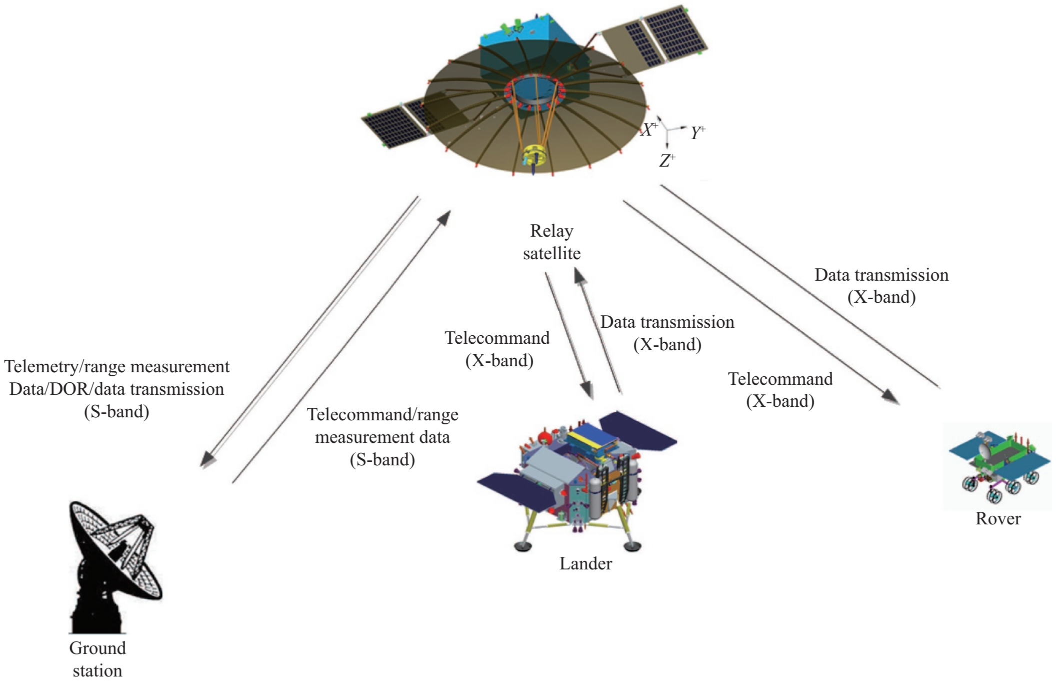

Figure 5 The relay communication link.

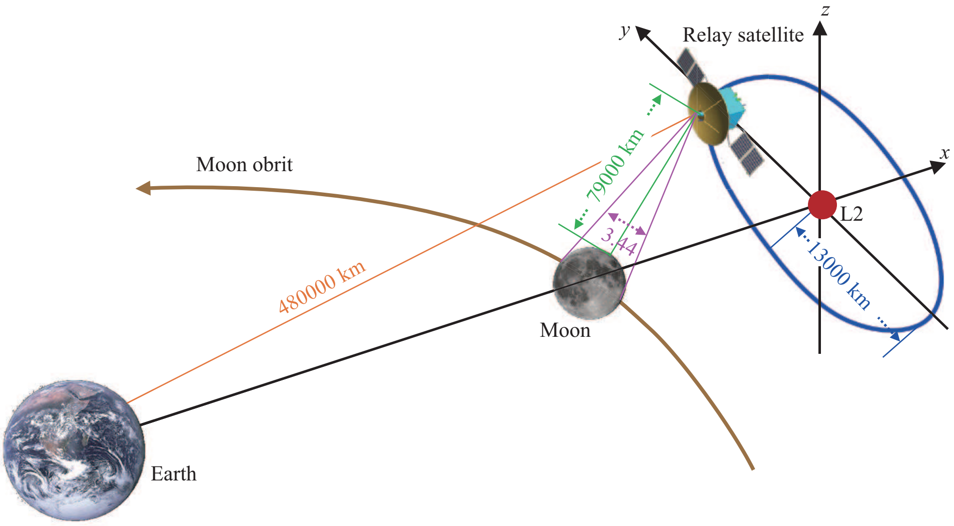

Figure 6 Earth-Moon Halo orbit configuration.

The first small-size, long-lifetime data relay communication satellite as well as a low-mass, high gain, large diameter and low temperature resistant antenna used in deep space, as shown in Figure 7 were developed. The reticular antenna material and molded surface keeping technology was broken through. As a result, the low temperature resistance ability of the antenna was improved from 2 to 6 h and the low temperature limit that the antenna can resist was increased from −180°C to −235°C. Hence, the safe operation and precise pointing under the environment of extremely low temperature are realized [15]. The result of numerical analysis for thermal deformation of the relay communication satellite reticular antenna is presented in Figure 8.

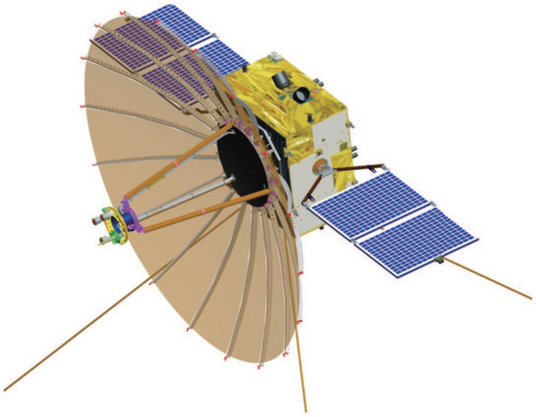

Figure 7 Queqiao relay satellite.

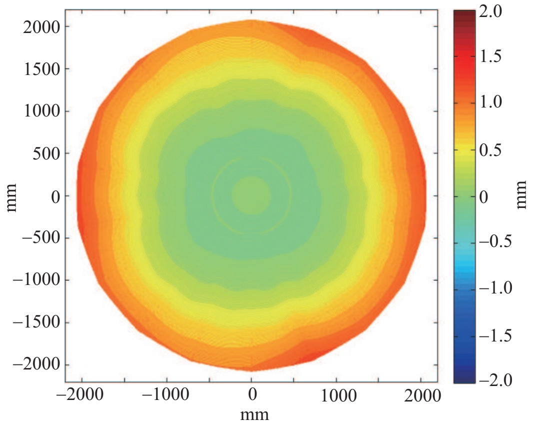

Figure 8 The numerical analysis result of thermal deformation of the relay communication satellite's reticular antenna.

3.2 Realized autonomous barrier-avoidance and high-precision landing on the complex terrain of the Moon's far side firstly

Since the terrain of the far side of the Moon is rugged, the landing area available for Chang'e-4 is only 5% in size of that of Chang'e-3. Thus, the joint orbit control method based on near Moon braking and circum Lunar correction double-layer iteration was invented. This enabled landing in the same narrow area at fixed time and point under multiple launch windows [16, 17].

In solving the drawback associated with safe landing for distance in the region of 7 km of track fluctuations, a control method for powered descent near vertical landing was proposed. This was aimed towards achieving an autonomous selection of landing site and accurate obstacle avoidance ability. The realization of key technologies was achieved such as the heterogeneous integration of the autonomous coarse obstacle avoidance, precise obstacle avoidance, the rapid autonomic fault diagnosis, and system reconfiguration [18–20]. The range of obstacle avoidance was as high as 300 m. While the powered descent process of the probe is shown in Figure 9, the three-dimensional elevation distribution of the landing zone is shown in Figure 10.

3.3 Realization of indigenous Chinese development of radioisotope thermoelectric generators (RTG) for the first time

The production of the highly toxic Pu-238 space by RTG pictorially shown in Figure 11, was another breakthrough. Additional breakthroughs are the 19 technologies in 4 categories on comprehensive experimentation and evaluation of safety for space applications, furthermore, indigenous Chinese development of RTG was realized. Key technologies such as RTG design, thermoelectric material development and high-efficiency heat transfer technology were conquered. The RTG was developed to generate stable electricity stably under the temperature difference of 210°C [21]. The development system and the technical specification of space nuclear power in China were constructed as a consequence of the critical problem relating to energy supply for future deep space missions was solved.

An automatic Lunar soil temperature measurement method based on RTG power supply during Moon night was proposed. This for the first time, led to the acquisition of day-night temperatures of the shallow layer of the Lunar soil on the far side of the Moon. Figure 12 shows the measured curves of day-night temperature on the Moon surface. From the figure, it can be seen that the lowest temperature measured was −196°C giving an insight to knowledge about the temperature condition of the Lunar environment.

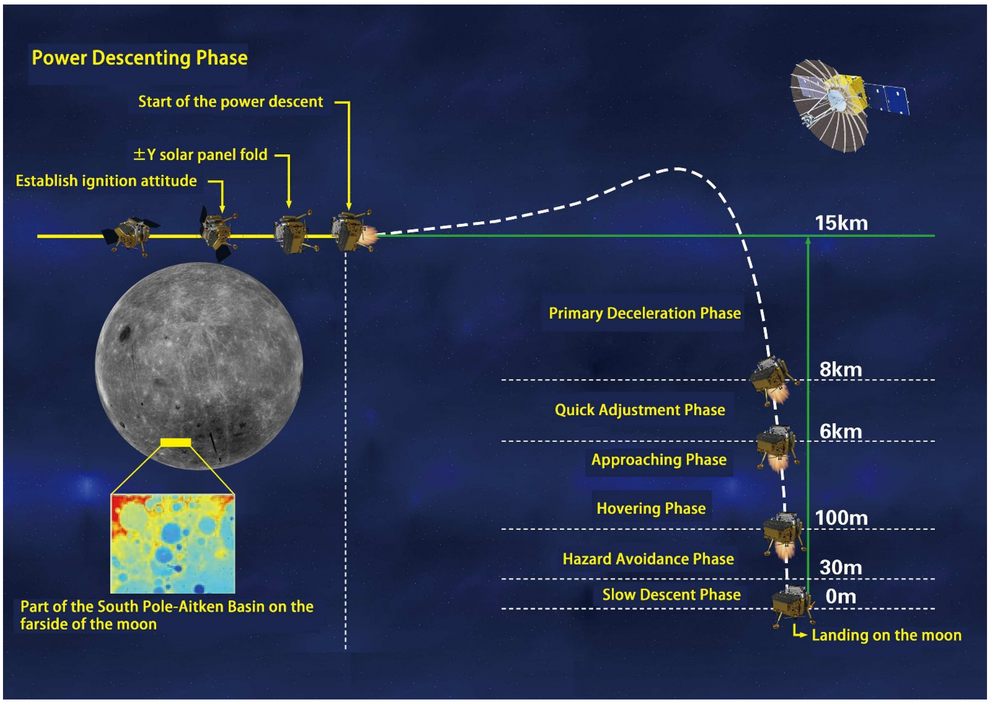

Figure 9 The powered descent process of the probe.

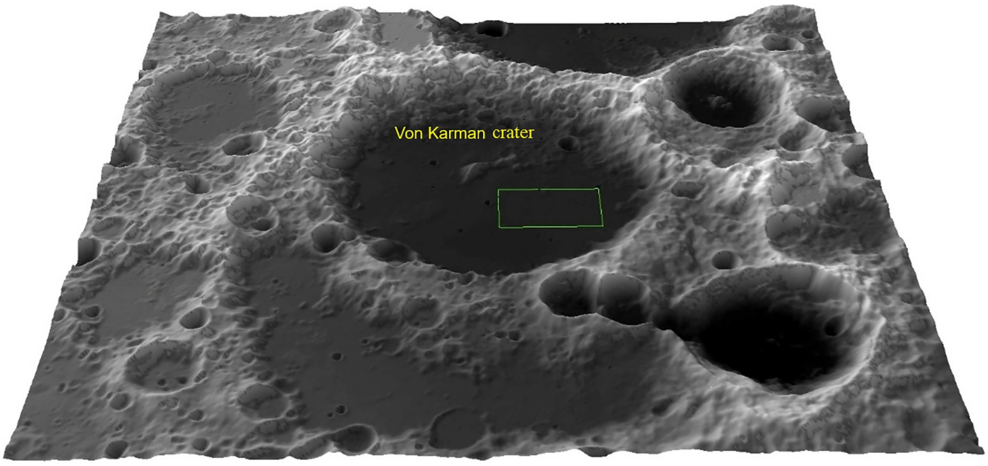

Figure 10 The three-dimensional elevation distribution of the landing zone.

3.4 Breakthroughs involving multiple-window reliable launch and combined navigation filter optimization technologies

A multiple-window optimization launch trajectory design was proposed and it was aimed towards achieving high-precision orbit entry requirements of the relay communication satellite. This resulted in a breakthrough for high-precision guidance technology in the multiple-interference integrated environment. It improved the trajectory entry accuracy of the launch vehicle CZ-4C by an order of magnitude [11, 22]. The flight height contrast of the launch vehicle was shown in Figure 13. The high-precision temperature control technology of normal temperature propellant was overcome, and the capability of launching at any time through five windows for three consecutive days is realized.

The combined navigation filter optimization technology was broken through. The accuracy of launch vehicle CZ-3B in orbit improved from 1000 km to 100 km when the apogee height reaches 420000 km. The disposal and support technology for delayed launch after injecting hydrogen-oxygen propellants was also

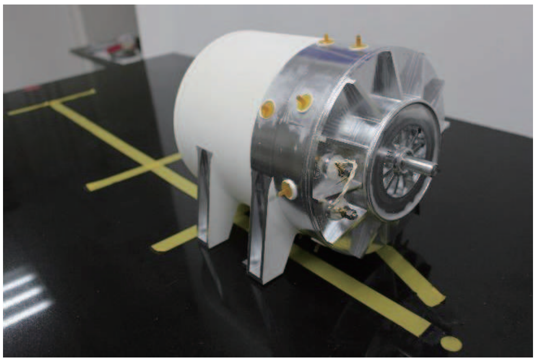

Figure 11 Space RTG.

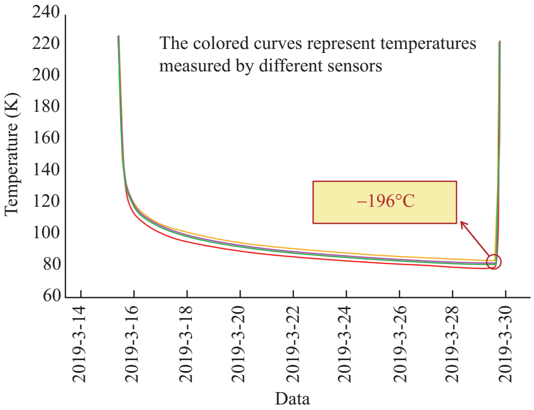

Figure 12 The measured curves of day-night temperature on Moon surface.

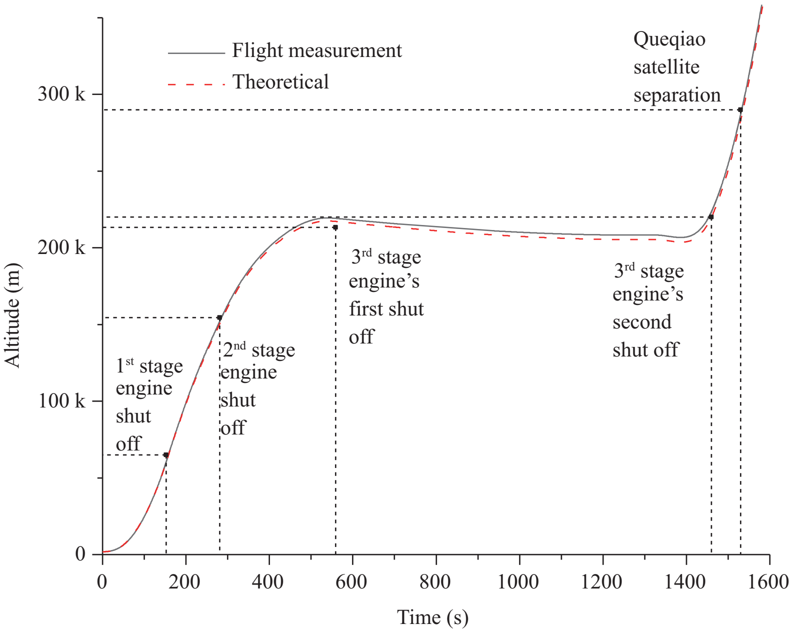

Figure 13 Flight height contrast of the CZ-4C launch vehicle.

broken through. The engineering capability of delaying launch for 24 h was acquired for the first time [23].

3.5 Realization of six-target TT&C for Lunar exploration and high-precision long-term control of the relay satellite in the Halo orbit

The multiple-target deep space TT&C scheme based on the global deployment of ground stations was proposed. This was a breakthrough related to multiple-channel parallel and multiple-mission concurrent processing. Also realized for the first time was reliable TT&C of up to six deep space targets. These include, among others, the relay communication satellite, the lander and the microsatellite during the mission period, as well as reliable whole-day multiple-target TT&C capability [24,25]. The multiple-target TT&C diagram of the Chang'e-4 mission is shown in Figure 14.

A high-precision orbit measurement and determination method was proposed. The method combines multiple ways, such as differential unidirectional ranging and regenerative pseudo-code ranging. The optimal maintenance technology of Halo orbit is based on the joint planning of momentum wheel unloading, orbit maintenance, and successive convergence was overcome [26–28]. High-precision orbit determination, prediction, long-term operation, and control under the weak constraint of dynamics at the Earth-Moon

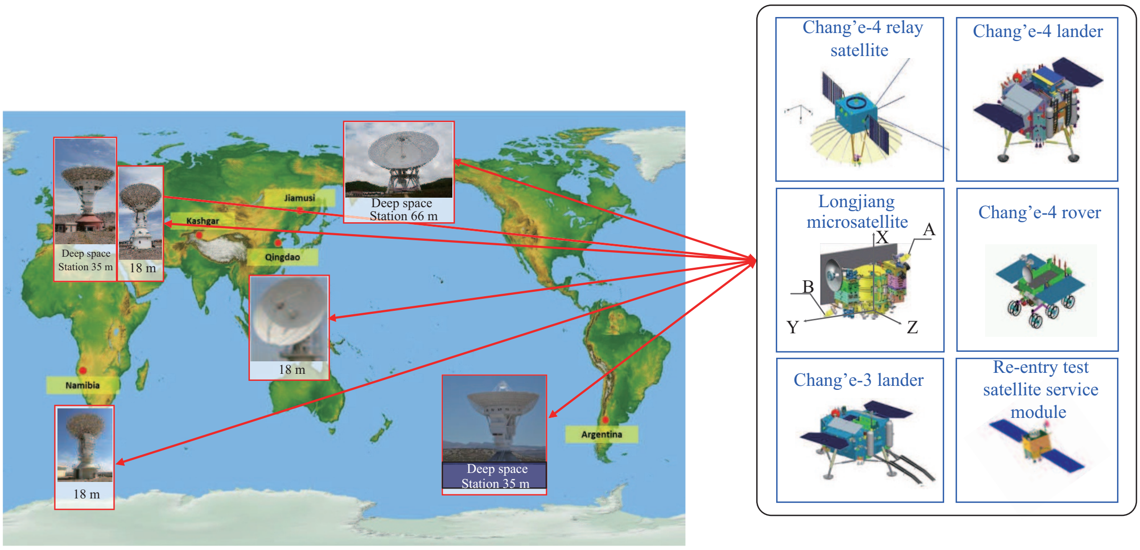

Figure 14 The multiple-target TT&C diagram.

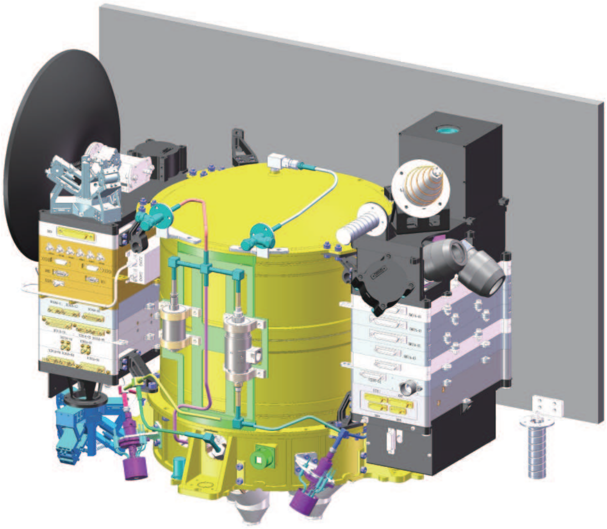

Figure 15 The "Longjiang" microsatellite.

L2 point were achieved. The propellants saved could increase the lifetime of the relay communication satellite from 3 to 10 years.

3.6 Breakthrough technology for the world's first circum Lunar microsatellite system

The microsatellite, "Longjiang" as shown in Figure 15, was launched together with the relay communication satellite. It was the world's first microsatellite which independently completed Earth-to-Moon transfer, braking near the Moon, and orbiting the Moon successfully. The microsatellite carried out myriametric wave astronomical observation in Lunar orbit as well as experimentation of VLBI high-precision orbit measurement and determination. It verified the deep space microsatellite platform technology and promoted the development and application of micro-nano satellites in the field of deep space exploration. In addition, the microsatellite was also equipped with an optical camera developed in Saudi Arabia to carry out imaging observations of the Moon.

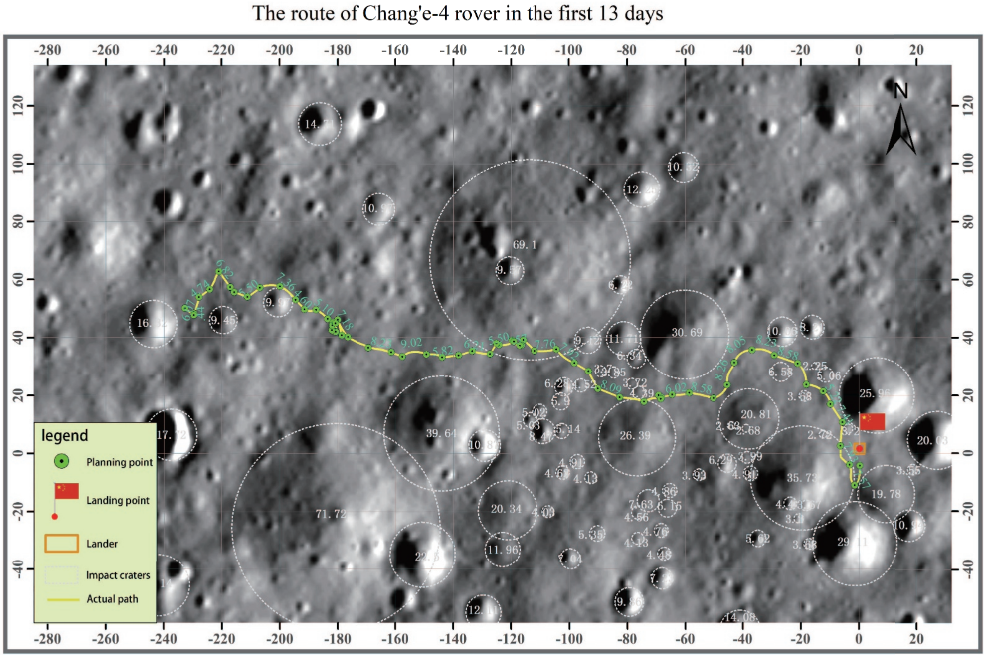

Figure 16 The traverse of the Yutu-2.

4 Main phased scientific results

The Chang'e-4 probe was equipped with 13 scientific instruments. These include, among others, eight scientific payloads and a payload for the popularization of science equip the lander and rover. So far, they have both been working steadily on the Moon for 17 Lunar days, setting a record for the longest movement on the Moon. They are, in addition, providing valuable first-hand data for science research. It is the first time of implementing the topography mapping, mineral composition determination and environmental exploration of the Moon's far side as well as the achievement of many original scientific contributions.

4.1 Revelation of the subsurface structure within a depth of 40 m below the Moon's far side

With the Lunar Penetrating Radar onboard the Yutu-2, the Lunar subsurface structure and regolith along the rover route has been investigated. An image of this is as shown in Figure 16. The study reveals for the first time a geological stratification structure below a depth of 40 m along the rover's route on the Moon's far side. According to radar images, the characteristic parameters of the material under the Lunar surface and an ejecta sequence were obtained along the 106-m route of the rover within a depth of 40 m. The three subsurface units with the different physical properties were identified. The study found that the underground material is made up of low-loss Lunar regolith and a large number of rocks with different sizes. The results of the study have greatly improved our understanding of the history of Lunar impact events and volcanism. These could shed new light on the comprehension of the geological evolution of the Moon's far side [29]. A schematic representation of the subsurface geological structure is as shown in Figure 17.

4.2 Preliminary analysis of the composition of deep-seated Lunar material

Data were acquired by the visible and near-infrared spectrometer on board the Yutu-2. It revealed that the spectral absorption characteristics of Lunar regolith at the Chang'e-4 landing site are obviously different from those of the Lunar mare basalts on the Moon's near side. This shows spectral characteristics of low-calcium pyroxene and suggests the existence of a large amount of olivine. Further analysis suggests

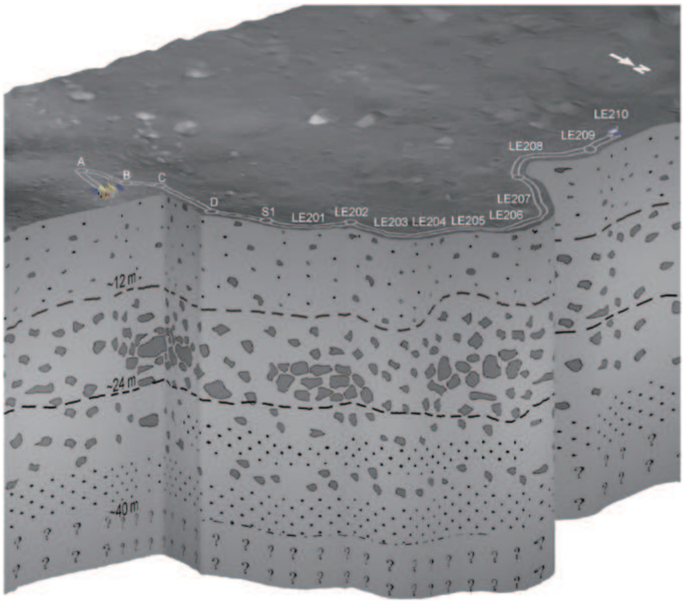

Figure 17 Schematic representation of the subsurface geological structure [29].

a relative abundance of olivine from the Lunar regolith at Chang'e-4's landing site. It is followed by low-calcium pyroxene, while high-calcium pyroxene was the least abundant. These may represent deep seated material potentially from the Lunar mantle [30].

The Yutu-2 rover not only acquired a large amount of spectral data on the Lunar regolith, and also investigated a less weathered rock which retained its spectral features. The regolith and rocks within the Yutu-2 roving area have similar spectral characteristics. This indicates that they may both be of the same origin. Their spectral characteristics are similar to the Finsen ejecta (see Figure 18). It is further confirmed that the composition of the regolith around Chang'e-4's landing area originated mainly from Finsen ejecta and represents the deep-seated material of the South Pole-Aitken Basin.

Based on the radiation transmission model, it is concluded that the rock is olivine-norite. This is inconsistent with the composition of the Lunar mantle. The fine-to-medium grain-sized texture of the rock suggests fast crystallization and is unlikely to be the original Lunar lower crust. This is probably due to the impact melt pond produced via melting the Lunar lower crust and upper mantle materials by the SPA basin-forming event. The observed rock is formed via crystallization from the melt pool [31,32].

4.3 Acquisition of space environment data from the Moon's far side

Chang'e-4's lander is equipped with the Lunar neutrons and dosimetry (LND) that was cooperatively developed by China and Germany to detect Lunar surface particle radiation and dose. The Yutu-2 rover is equipped with the Sino-Swiss Advanced Small Analyzer for Neutrals (ASAN) for observing the energy neutral atom of the roving site. The ASAN measured the energetic neutral atoms (ENAs) at Chang'e-4's rover's exploration area. The results from ASAN showed the ENA energy spectrum and albedo for energy above 30 eV were in good agreement with previous measurements from Chandrayaan-1 and IBEX. Furthermore, the majority of these ENAs were considered to be back-scattered hydrogen ENAs. The ENA flux and albedo for energy below 30 eV is generally higher than the results of the two previous missions. The reason could be that more sputtered lower-energy ENAs were generated because of local regolith features (e.g., porosity, grain size and composition) at the landing area.

The LND experiment aboard the Chang'e-4 lander has made the first ever measurements of radiation exposure to both charged and neutral particles on the Lunar surface. An average total absorbed silicon dose rate of 13.21 ± 1.01 μGy/hour and a neutral particle dose rate of 3.05 ± 0.43 μGy/h were measured. Additionally, an average quality factor $\langle Q\rangle = 4.32\pm 0.65$ was obtained. After multiplying the absorbed charged-particle dose rate (in water), with the measurement given by $\langle Q\rangle$, the GCR dose equivalent rate

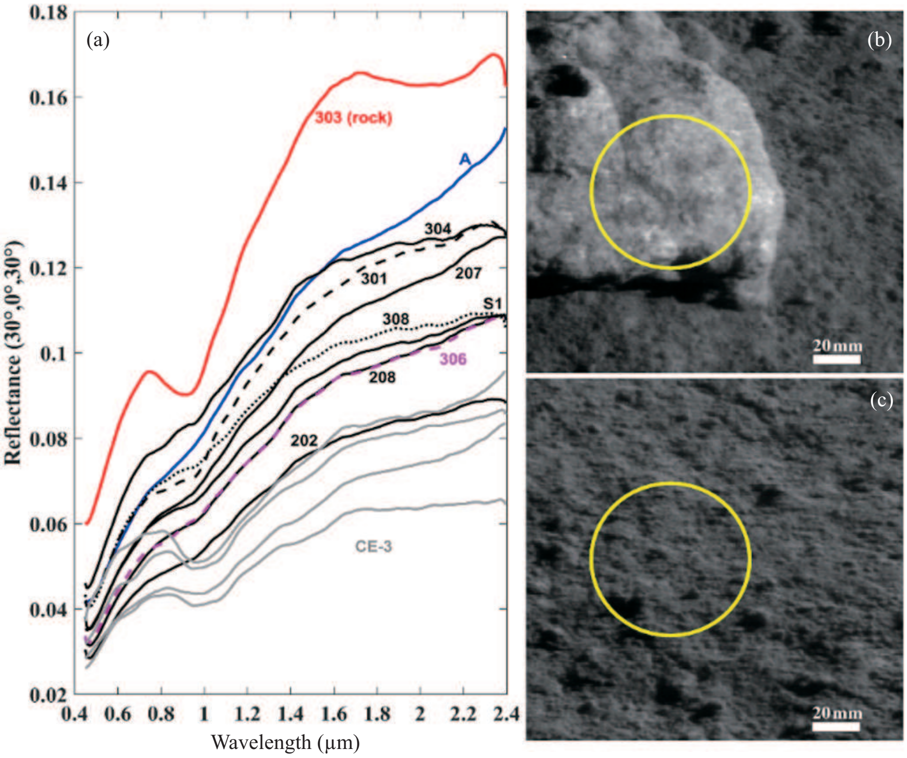

Figure 18 Components of Lunar rocks [31]. (a) VNIS spectra of the rock and Lunar regolith measured by Chang'e-4. 4 other spectra (in grey color) of the basaltic Lunar regolith measured by Chang'e-3 are shown for comparison. (b) and (c) are the CMOS images of the rock (labeled as 303) and the Lunar soil (labeled as 207) at 0.75 μm observed by VNIS's imaging spectrometer, respectively. The yellow circle is a short wave infrared (SWIR) field, and the scale bar is 20 mm.

of 57.06 ± 10.57 μSv/hour from charged particles is obtained. The understanding of the characteristics and change in the space environment around the Moon's far side is of great scientific value. It will provide support for future crewed Lunar missions.

4.4 Acquisition of space signal data with low-frequency radio spectrum for the first time

A very low-frequency radio spectrometer (VLFRS) was developed and mounted on the Chang'e-4 lander. After the VLFRS landed on the Moon's farside, three component high-resolution time-varying waveforms of very low-frequency radio waves (10 kHz–40 MHz) were acquired. It was the first time an ultra-wideband very low-frequency radio astronomical signal was observed on the Moon's farside surface. The study of the data is of great significance for understanding the low-frequency radio of solar bursts as well as the low-frequency radiation environment of the Lunar surface [5, 33, 34].

4.5 Conducting of a series of scientific experiments

Conquering the key technologies was an important milestone. These include living organism immobilization, autonomous temperature control and light-guiding in the complex environment on the Lunar surface. Next was the deployment of a payload for carrying out scientific-popularization biological experiments. For this, a combination of animals, plants and microbes was loaded onto the lander. Biological incubation experiments were carried out on the Lunar surface, and the germination process of cotton seeds in a closed environment was successfully observed [10].

The angular reflector that met the requirements of relay satellite laser ranging was successfully developed. It broke through key technologies such as high-precision pointing and tracking of ground-based laser ranging telescope. It was the first time in history that reflective laser ranging beyond the Earth-Moon distance was carried out. It significantly improved the accuracy of deep space satellite laser ranging. A Lunar laser ranging experiment was performed for the first time in China. This was achieved using the modified 1.2 m telescope at the Yunnan Observatory of the Chinese Academy of Sciences and the newly-built 1.2 m telescope at Zhongshan University in Zhuhai, Retro-reflectors were emplaced on the Moon's surface during a series of missions launched in the 20th century. The missions include those of Apollo-11, Apollo-14 and Apollo-15 launched by the United States and the Luna-17 and Luna-21 missions launched by the Soviet Union [35–37].

5 Conclusion

Since the successful implementation of the Chang'e-4 project in 2018, a number of technological breakthroughs and significant phased scientific achievements have already been made. More than 150 patents have been authorized. More than 140 peer-reviewed papers have been published in *Science China Series*, *Nature*, *Science*, and other major journals and conferences at home and abroad. In addition, four books have also been published. These achievements have promoted the development of space radio astronomy, planetary science, and other related disciplines in China. The Chang'e-4 project has achieved a number of capabilities. These include, inter alia, full Moon arrival, autonomous precision landing, relay communication at the Earth-Moon L2 point, launching with high precision and high reliability, multiple-target Lunar TT&C, and indigenous development of space RTG. In addition, the project has driven the advancement of technologies in other fields such as new energy, new materials, new processes, artificial intelligence and advanced electronics. It has great practical significance and far-reaching historical influence on making China a space, scientific and technological power, as well as enhancing national cohesion.

For the first time in the history of the Lunar exploration programme of China, a popular science payload was selected out of proposals from college and middle school students. This greatly stimulated the enthusiasm of teenagers for space exploration. Also for the first time in the history of the Lunar exploration programme of China, scientific payloads from foreign countries such as Germany and Saudi Arabia, were launched onboard spacecraft of the Chang'e-4 project. A mechanism for international collaboration and sharing of scientific data has been established.

Chang'e-4's landing site was named Tianhe Base by the International Astronomical Union, making it the second base to be named since Apollo 11's landing site was named Tranquility Base. Chang'e-4's team was awarded the only team gold medal in 2019 by the Royal Aeronautical Society of the United Kingdom. This made it the first time in its 153-year history that the society has awarded a prize to a Chinese project. The Chang'e-4 mission was awarded the outstanding mission of the year 2019 by the International Moon Village Association and the 2020 IAF World Space Award by International Astronautical Federation. The project has significantly increased China's international influence.

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