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Landing Site Selection and Overview of China's Lunar Landing Missions

Jianjun Liu[1,2] · Xingguo Zeng[1] · Chunlai Li[1,2] · Xin Ren[1] · Wei Yan[1] · Xu Tan[1] ·
Xiaoxia Zhang[1] · Wangli Chen[1] · Wei Zuo[1] · Yuxuan Liu[1] · Bin Liu[1] · Dawei Liu[1] ·
Qin Zhou[1] · Ziyuan Ouyang[1]

Abstract Landing site selection is of fundamental importance for lunar landing mission and it is closely related to the scientific goals of the mission. According to the widely concerned lunar science goals and the landing site selection of the ongoing lunar missions; China has carried out the selection of landing site for a series of Chang' E (CE) missions. Under this background, this paper firstly introduced the principles, process, method and result of landing site selection of China's Lunar Exploration Program (CLEP), and then analyzed the support of the selected landing sites to the corresponding lunar research. This study also pointed out the outcomes that could possibly contribute to the key lunar questions on the basis of the selected landing sites of CE-4 and CE-5 such as deep material in South Pole-Aitken (SPA) basin, lunar chronology, volcanic thermodynamics and geological structure evolution history of the Moon. Finally, this approach analyzed the development trend of China's follow-up lunar landing missions, and suggested that the South Pole Region of the Moon could be the landing site of high priority for the future CE missions.

Keywords Chang' E mission · Lunar exploration · Landing missions · Landing site selection

✉ X. Zeng
zengxg@nao.cas.cn

✉ C. Li
licl@nao.cas.cn

J. Liu
liujj@nao.cas.cn

[1] Key Laboratory of Lunar and Deep Space Exploration, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China

[2] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing, 101408, China

1 Introduction

Since the beginning of the 21st century, Europe (SMART-1), Japan (SELENE), India (Chandrayaan-1, Chandrayaan-2), United States (LRO, GRAIL, LADEE), Israel (Beresheet), and China (CE-1, CE-2, CE-3, CE-4) have carried out several lunar exploration missions acquiring many new discoveries and achievements (Foing et al. 2007; Kato et al. 2010; Goswami and Annadurai 2009; Petro and Keller 2014; Zuber et al. 2013; Horányi et al. 2014; Clery 2019; Ouyang et al. 2010; Li et al. 2019a; Li et al. 2019b).
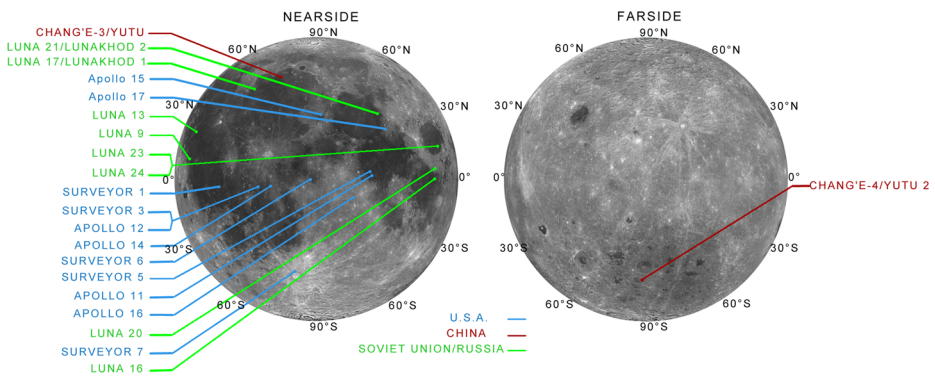
In 2005, during the demonstration of China's Lunar Exploration Program, Ouyang et al. summarized 14 key science concepts which are closely relevant to lunar exploration (Ouyang et al. 2005; Li et al. 2019b). In 2006, a new understanding of the lunar geologic structure and its evolution was proposed by a number of planetary scientists, and 9 key concepts for current lunar science were summarized according to the comprehensive research results obtained based on remote sensing data from Clementine and Lunar Prospector missions, exploration data from 6 Apollo manned lunar exploration missions, and laboratory analysis of returned lunar samples and meteorite (Jolliff 2000; Jolliff et al. 2006). In 2007, 8 key science concepts were addressed in the report "Scientific Context for Exploration of the Moon" (NRC 2007) and several science goals were added in 2011 (NRC 2011). In 2017, Lunar Exploration and Analysis Group (LEAG) updated and improved 11 core scientific concepts of lunar exploration, and proposed research suggestions for these scientific concepts in "Advancing Science of the Moon" (LEAG 2017) based on the NRC report. In 2019, European Space Agency (ESA) also proposed 7 lunar science activities of higher priority for the next decade (ESA 2019).

In order to promote the study of above mentioned lunar science concepts, many kinds of lunar exploration missions have been carried out by the mankind. Some of the most effective ways among them include landing on the surface of the Moon, carrying out in situ exploration or sampling return, and obtaining the first-hand lunar exploration data or lunar samples from the landing site. It is necessary to perform the study of landing site selection for such lunar missions to answer questions like which location on lunar surface might be suited for safe landing or what scientific goals are likely to be achieved. Section 2 of this paper summarizes the existed landing sites on the lunar surface and introduces the prior landing sites of the future missions. Section 3 mainly introduces the implementation plan of China's lunar exploration upon which the selection principles, process and method will be introduced. Section 4 introduces the detailed selection results of CE-3–CE-5 missions. The characteristics of these landing sites and the exploration results that already have been or expected to be obtained of these missions were also analyzed. At last, Section 5 summarizes the promotion of the selected CE landing sites on some lunar key scientific concepts and provides the prospects regarding the workflow of future landing site selection and the potential landing site for China's future lunar missions.

2 Overview of Lunar Landing Site Selection

To date, there have been 20 successful manned and unmanned soft landing missions on the Moon, including Surveyor series missions, Apollo series missions, Luna series missions and CE series missions.

It can be seen from Fig. 1 that, all lunar soft landing sites are located in the lunar near side in the middle or low latitudes ($-45°$ S–$45°$ N) except for CE-4. Constrainedly the spatial

Fig. 1 Distribution of the available successful lunar soft landing sites (Redraw according to Li et al. 2019b)

distribution of the available landing sites, many core lunar science goals could not be fully accomplished (LEAG 2017). Several reasons can account for this. Firstly, there were too few landing sites in the lunar far side. The corresponding field work such as in situ dating, in situ elemental and mineralogical analysis, and low frequency radio observation of lunar far side could not be well conducted, which will impede the study of some science goals provided in NRC (2007). For example, the science concepts 1 of NRC (2007) (The bombardment history of the inner Solar System is uniquely revealed on the Moon) cannot be answered since the biggest impact basin of the Moon (SPA) is in the lunar far side lacking effective in-situ exploration. Secondly, no landing sites are located at the high latitude region (60° N–90° N or 60° S–90° S) leading to the insufficient support to the in situ analyses and the return of cryogenically preserved samples of the lunar polar region, which will impede the study of science concept 4 in NRC (2007): The lunar poles are special environments that may bear witness to the volatile flux over the latter part of Solar System history. Thirdly, according to the Mare Unit classification method (Chevrel et al. 2002), the lunar mare could be classified into M1-M5 units by iron, Titanium (Ti), and Thorium (Th) contents. M1 and M2 are high-Ti mare basalts with different Th content. M3 and M4 units also of different Th content are contain less Ti than M1 and M2 sites. M5 is the unit with very low Ti levels, and the lowest Fe content as well. Lunar samples from M1, M3 and M4 were collected in the Luna and Apollo missions, but the samples from M2, M5 were still not available (Kring and Durda 2012). The lack of specific type of mare rocks will impede the study of science concept 3 in NRC (2007): Key planetary processes are manifested in the diversity of lunar crustal rock. Fourthly, according to the research from LPI-JSC (Lunar and Planetary Institute, Johnson Space Center) Center for Lunar Science and Exploration, the youngest lunar samples obtained from the Apollo and Luna sample return missions have an age of 3.08 Ga, and the youngest lunar meteorite (basalt) has an age of 2.8 Ga (Fagan et al. 2002). The lack of younger lunar samples could affect the reliability of the calibration curve generated on the basis of the crater formation rate and absolute crater age in lunar chronology (Kring and Durda 2012), and thus impedes the study of science concept 5 in NRC (2007): Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.

In order to further promote the research on the key scientific concepts of the Moon, many countries, institutions and scientists are planning for the next generation of lunar surface landing missions and conducting research on the selection of landing sites.

According to the importance degree of scientific goals provided in NRC report (NRC 2007), NASA has selected several high priority potential areas for future landing missions (Jawin et al. 2019). LPI-JSC has also carried out a detailed study on the selection of landing site for the first seven scientific goals and the corresponding sub items proposed by NRC (Kring and Durda 2012). In 2019, NASA announced that it will send the astronauts to the Moon in 2024 to land in the South Pole (NASA 2019; Crawford et al. 2012). The corresponding work of landing site selection is also in progress.

Aiming at lunar science goals related to lunar rock types, age, distribution and origin, Flahaut et al. (2012) provided an approach to optimize science-rich lunar landing site selection. In that research, multi-source remote sensing observations data are firstly used to study the distribution of main geologic unit and composition of the lunar surface. The Proximity Model (Wieczorek and Zuber 2001; Cahill et al. 2009) and the requirements of science issued to the landing site were discussed next and the selected landing site is finally proposed using the Geographic Information System (GIS) tools. Flahaut et al. (2019) further investigated the regions of interest in the lunar polar region. The landing site was selected with the aim of the detecting the distribution of water ice based on the terrain conditions, conditions and other factors for future missions such as Luna-25, Luna-27 and Lunar Prospecting Rover. To study special space environment in the polar region of the Moon, Lemelin et al. (2014) selected the landing site by considering the areas of H enrichment, the distance from the Permanent Shadow Region (PSR), the maximum and minimum annual average temperature, and the convenience of slope navigation. Many other scientists have also conducted numerous work regarding landing site selection at SPA basin (Koebel et al. 2012) or specific crater such as Schrodinger (Potts et al. 2015).

Lunar and Planetary Institute (LPI) and ESA had planned to land in the SPA basin via ESA Lunar Lander Mission, attempting to test the ability of precise soft landing, to avoid dangerous areas and to conduct lunar surface surveys. The light condition, communication condition, terrain slope, circular crater, boulder and shadow on safety were analyzed when selecting the landing site. A landing area with the best illumination and the highest safety was preferred (De Rosa et al. 2012).

Russian Federal Space Agency (ROSCOSMOS) planned to select landing sites from SPA basin for Luna-25 mission. From the perspective of science, the mission aimed at finding water ice and related substances. From the perspective of engineering, factors such as thermodynamic conditions, terrain slope, ground station communication conditions, lighting conditions (energy supply) and etc. were considered (Djachkova et al. 2017).

The landing site selection for SELENE-2 and subsequent lunar missions, Japan Aerospace Exploration Agency (JAXA) prefers representative geological units such as Procellarum KREEP Terrane (PKT), Feldspathic Highlands Terrane (FHT), SPA basin or sites with "fresh outcrops" (i.e. intact lunar rock formations). Accordingly, they selected four types of candidate landing sites including Pole regions consist of highlands and volcanic area, SPA basin, Central peak of large crater in PKT area, and Highland on the lunar far side (Hashimoto et al. 2011).

Indian Space Research Organization (ISRO) conducted a study on the Chandrayaan-2 landing site selection close to 70° S (Amitabh et al. 2018). The candidate landing sites were selected from the perspective of engineering implementation. To ensure the safe landing and rover movement, factors such as terrain slope, obstacles, crater, lighting conditions, communication conditions and terrain shadow were taken into account.

	Flown missions 2004-2020				Flight ready mission 2020	Missions in development 2020-2030			
CE-1	**CE-2**	**CE-3**	**CE-5T**	**CE-4**	**CE-5**	**CE-6**	**CE-7**	**CE-8**	
2007.10	2010.10	2013.12	2014.10	2018.12	2020	TBD	TBD	TBD	
Orbiter	Orbiter	Lander/rover	Relay/lander rover	Relay/lander rover	Sampling return	Sampling return	Lander/station	Lander/station	
200-km-high orbit	100-/15-km high orbit	Mare Imbrium	Earth-Moon	Crater Von Kármán	Ocenus Procellarum	South Pole	South Pole	Location??	Robotic and manned exploration
Global Survey	High-resolution Global survey	Lunar surface survey	High-speed Earth return	Far-side surface survey	Lunar sample	Lunar polar samples	Lunar scientific research	Lunar scientific research	

Fig. 2 The road map of China's Lunar Exploration Program (Redraw according to Li et al. 2019b)
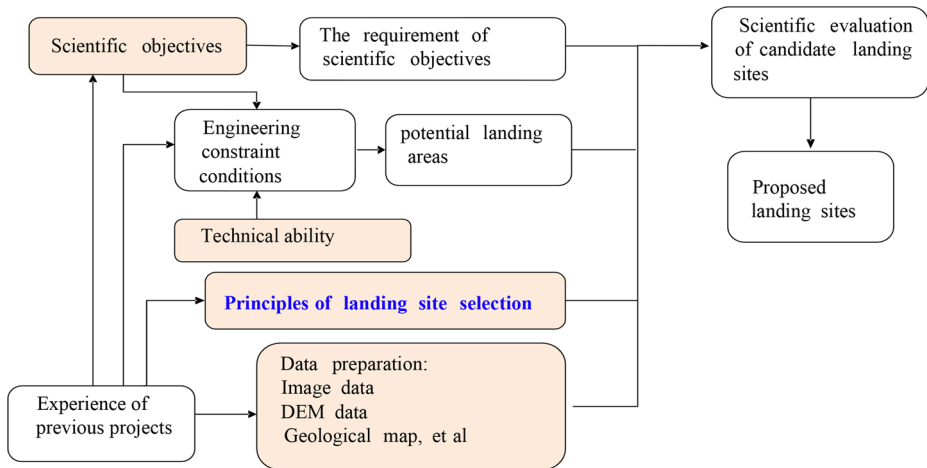
3 Landing Site Selection of CLEP

3.1 Road Map of China's Lunar Landing Missions

Based on the lunar science research progress and China's scientific, technological and economic conditions, China National Space Administration (CNSA) decided to take "unmanned exploration" as the first phase of lunar exploration. This phase consists of three steps, corresponding to "orbiting", "soft landing" and "sampling return" to implement the general planning roadmap of Chang' E program. After the first phase exploration, a followup lunar exploration plan was proposed. The working steps are designed as: 1) 'Reconnaissance', reconnaissance of the lunar environment and resources; 2) 'Construction', establishment of long-term basic scientific research platform; 3) 'Utilization', technical verification of exploitation and utilization of resources (Pei et al. 2015). Three missions were initially planned to be implemented, including CE-6, CE-7 and CE-8. A proto type of lunar robotic research station will be built in the south polar area by 2030 (Li et al. 2019b).

Started from CE-3 mission, landing site selection is considered as the most important part in the top-level design of the mission. Selection of landing site is carried out at the same period with the overall design of the mission, dedicated to the fulfillment of scientific and engineering objectives. The road map of CLEP is shown in Fig. 2.

3.2 Method and Process of Landing Site Selection

The general process of landing site selection for CLEP is shown in Fig. 3. Firstly, the scientific objectives of the mission are put forward based on the experience of successful exploration missions; the engineering constraints are proposed according to the current technical capabilities; the corresponding data are prepared according to the needs of missions, and the principles of selecting specific landing site are formulated. Secondly, according to the scientific objectives, the specific requirements for the landing site such as geographic location, geological conditions and space environment are put forward. According to the requirements of the safety implementation of the mission, the engineering constraints on the geographic location, geological conditions and space environment are also refined in terms of engineering reliability. The potential areas meeting the engineering implementation conditions are screened out through this way. After that, based on the principles of landing site selection, the potential landing sites are scientifically evaluated, scored and sorted with a designed lunar landing site sorting model (Zeng and Mu 2017). Finally, several areas with top scores are selected as the proposed landing sites.

Fig. 3 Flow chart of landing site selection in CLEP

3.2.1 Principles of Landing Site Selection

When selecting the landing site for CLEP, the feasibility of scientific and engineering objectives are two major concerns. The selection principles can be summarized as follows.

(1) Technical feasibility

In terms of engineering safety, reliability and technical feasibility, the selection of the landing site should comply with following principles:

Due to the capability of CE spacecraft, the location of the landing sites should not exceed the geographic area where the spacecraft could reach before the total propellant is consumed. For example, the CZ-3B rocket can launched a probe with a maximum weight of 3.78 t into earth-moon transfer orbit. The dry weight of the CE-3 (lander and rover) is 1.22 t and the total mass of propellant is about 2.56 t (Sun et al. 2014; Zhang et al. 2014). Thus, a proposed landing site with a less propellant consumption would be favorable.

Due to the capability of launch system of CLEP, the location of the landing sites will affect the choose of the launch window, for example in CE-3 mission, a launch window with a duration longer than 3 consecutive days is suggested, and 5–6 launch windows in a month is favorable for a proposed landing site.

Due to the Telemetry, Track and Command (TT&C) capability of CLEP, the location of the landing site should not exceed the geographic area where the spacecraft can communication with the TT&C ground station. For example, In CE-3 mission, two ground stations which located at JiaMusi (JM01) and KaShi (KS01) were used in the TT&C observation for the spacecraft. In CE-4 and subsequent missions, a new ground station located at South American (NM01) was added (Lu et al. 2018; Wu et al. 2020). During the flight to a proposed the landing site, the spacecraft should be able to communicate with at least two of those ground stations in some key TT&C observation arc such as orbit change, posture adjustment, and descent process.

Due to the safety requirements of the spacecraft and scientific instruments, the landing sites should be within the geographic area which could provide a safe environment for lander landing, rover moving and instruments working. For example, the terrain should not exceed 8° which safe for lander landing and rover moving (Sun et al. 2014). The altitude

is recommended to be 30°–60° to ensure that it is safe for accessing solar energy, and the temperature is also safe for the instruments working.

(2) Scientific objectives realization

To guarantee the scientific goals could be achieved, it is required to select lunar surface areas with more scientific detection targets and contents in a relatively small spatial extent. It also requires that the planned scientific goals could be realized by conducting scientific exploration in the selected landing sites such as advancing the research on the geological structure of the Moon, promoting the study of compositional and physical properties of lunar rocks and soil, and conducting the research of formation and evolution of the Moon. For example, to determine the composition of the lower crust and deeper material, SPA is the preferred landing site. To establish a precise absolute chronology, the landing site would be better in the youngest or oldest region on the surface of the Moon. To investigate the earth plasma on the Moon, the landing site would be better in the lunar near side. To conduct Very Low Frequency Radio surveys, the landing site would be better in the lunar far side.

To ensure the scientific objectives could be achieved meaningfully, the following landing sites are more favorable by CLEP: 1) have research hotspots and scientific uniqueness; 2) have not been explored by previous historical missions; 3) beneficial to the sustainable development of China's future lunar landing missions.

According to the principles of landing site selection, we made a preliminary selection of the landing area mainly from two aspects: technical feasibility and scientific objective realization. In particular, the selection of landing sites was made in response to the above-mentioned (Sect. 2) considerations such as in the area of different Mare Unit, the far side of the moon, the relatively youngest and oldest areas on the lunar surface, the high latitudes and the Polar Regions.

According to the technical and scientific constraints, the necessary quantitative analysis and comparison should be carried out and the landing site could be optimized. Commonly, there are multiple rounds of selection during the landing site selection process to balance the technical feasibility and scientific interests. Firstly, landing areas meeting the strict criterion of engineering constraints would be selected and introduced. Then, the scientists would propose some interested landing sites from the selected areas according to the scientific objectives of the mission. After that, the proposed landing sites would be evaluated and scored with the ranking model. In each round, the suggestion from the engineers and scientists will be thoroughly discussed.

3.2.2 Scientific Constraints

Based on the available experience in landing site selection, the scientific constraints for CE missions are considered from the aspect that whether the scientific objectives could be possibly achieved. Typical scientific constraints are listed as follows (can be expanded according to the needs of the mission).

The Geomorphologic and Geological Characteristics   We mainly consider 1) Whether there are typical and varieties of geomorphologic features and geological units within the exploration area; 2) Whether it is of special value such as located in the boundary of geologic units with different ages; 3) Whether it is located in the boundary between Mare and Highland; 4) Whether it has volcanic features such as volcanoes, domes and etc; 5) Whether it possesses characteristics of older or younger geologic layers, older or younger rock types, water ice distribution and etc.

Distribution of Lunar Resources   We mainly consider from the perspective of lunar resources utilization. The selection of landing site should consider whether the area has the potential for resources utilization;

Space Environment Characteristics   We mainly consider whether the landing site can reveal special characteristics of lunar environment such as gravity, magnetic field and other environmental features;

The Demand for Moon Based Astronomical Observation   We mainly consider whether the landing site is beneficial for the long-term astronomical observation of the interested scientific objects.

3.2.3 Engineering Constraints

Based on the international experience in landing site selection, the engineering constraints are considering from the perspective that whether the landing missions could be safely implemented. By that means, the main engineering constraints are listed but not limited to as follows. (Since the engineering conditions for each mission are different, engineering constraints could be expanded according to the needs of the mission, and some specific constraints for CE lunar landing missions will be discussed in Sect. 4.)

Topographic Slope and Terrain Obstacles   Mainly related to the safety of soft landing and rover transverse. For example, steep slope, craters, boulders and rocks might be encountered in the course of soft landing and rover transverse. Therefore, the areas with excessive distribution of those targets should be avoided. The roughness of the surface should not be too large so that the energy consumption of the rover could be acceptable, and the rover could be able to transverse more easily. In the landing site selection for China's lunar missions, the average topographic slope of a proposed landing area should not exceed $8°$, and a relative larger percentage of area with slope $<8°$ is favorable (Sun et al. 2014).

Communication Ability   Mainly related to the ability of data communication between the spacecraft and the ground control center. It should be considered whether in the selected landing site it is possible to ensure the key TT&C observation arc and the communication ability between the spacecraft and the ground station. The possible communication time from the ground stations to the landing site will be calculated, and the area with better communication ability is favorable for the landing site. For example, the visual time of space-ground communication will be constrained by the latitude and longitude of landing site, and the rotation angle range of the lander communication antenna. The influence of terrain occlusion on communication should be also analyzed.

Temperature   Mainly related to the thermal control of the space craft. It should be considered whether the spacecraft can survive and detect as the lunar surface temperature varies in the selected landing area. For the safety of the scientific payloads, those areas with high temperature and large temperature variation should be avoided. It is known that the lunar surface temperature is directly related to the Solar Elevation Angle (SEA). In China's lunar missions, the SEA is suggested to be $30°$–$50°$. High latitude ($>60°$) which would possibly exceed the SEA is commonly not recommended. In addition, it has been calculated that temperature variation will be relative large if the latitude is lower than $30°$. Therefore, the latitude should be neither too high nor too low, and commonly a latitude ranging from $30°$–$60°$ is recommended for a proposed landing area.

3.2.4 Ranking Model for Landing Site Evaluation

Based on the scientific and engineering constraints proposed in Sect. 3.2.2 and 3.2.3, a multi-factor weighted ranking model (Zeng and Mu 2017) for landing site evaluation is proposed. In terms of scientific indicators, the standard for the evaluation is based on the geomorphologic, geological, spatial environment characteristics and the possibility to fulfill the scientific objectives. The evaluation result is mainly divided into four grades: excellent, good, fair and poor, each with a different score. In terms of engineering indicators, the evaluation is based on the proximity to the engineering requirements for topographic slope, terrain roughness, solar elevation angle, obstacle density, communication time, temperature, and etc. The evaluation result is also divided into excellent, good, fair and poor. Each grade is given a different score. Finally, the weighted scores are calculated by using a fuzzy based evaluation algorithm, which integrates scientific and engineering factors. The evaluation method considers multiple factors and uses the theory of fuzzy sets to evaluate its advantages and disadvantages. The basic idea is to assume two finite domains:

$$U = \{u1, u2, \ldots un\} \tag{1}$$

$$V = \{v1, v2, \ldots vm\} \tag{2}$$

Here U is a comprehensive set of evaluation indicators, which includes the scientific indicators or engineering indicators; V represents a set of scores, such as {excellent, good, fair, poor}. The evaluation is a problem of fuzzy transformation:

$$X * R = Y \tag{3}$$

In equation (3), '*' means synthesis operation, X is a subset on U, the evaluation result Y is a fuzzy subset on V, and the fuzzy relation R can be regarded as a fuzzy transformer through evaluation. The final total score is obtained by ranking the results and weighting calculation, and the candidate landing sites are those with the top scores.
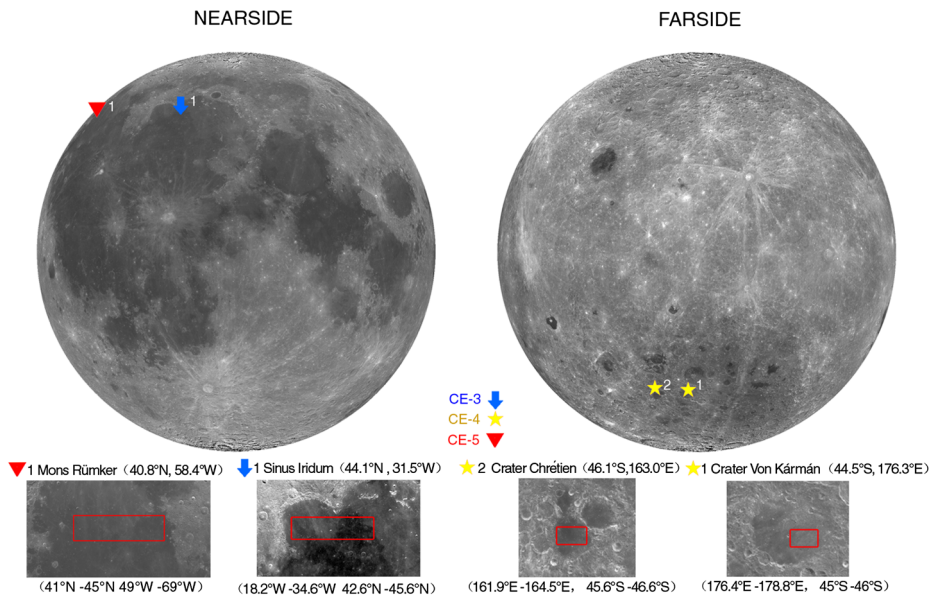
4 Proposed Landing Sites Selected for CE Missions

According to the above principles, process and method of landing site selection; CLEP has carried out the landing site selection for CE-3, CE-4, and CE-5 missions. The distribution of the selected landing sites is shown in Fig. 4. The detailed description of each mission is described in the following sections.

4.1 CE-3 Landing Site Selection

CE-3 mission is China's first soft landing exploration on the Moon, which is designed with priority to land on the near side of the Moon. The spacecraft has a lander and a rover (also known as the Yutu Rover) (Li et al. 2015). Its main scientific objectives are: 1) Investigate the surface topography and geological structure; 2) Investigate the material composition and available resources of the surface; 3) Explore the space environment in Sun-Earth-Moon orbit, and Conduct the Moon based optical astronomy observation.

In order to achieve the scientific objectives of CE-3, we initially selected five candidates in the near side of the Moon considering the technical capability of CE-3 spacecraft, which are Mare Nectaris, Mare Humorum, Crater Aristillus, Crater Kepler, and Sinus Iridum. The

Fig. 4 Candidate landing sites selected for CLEP landing missions, the red rectangles stands for the target area of the landing sites

specific location information is shown Table 7 of Appendix A. These candidate landing sites tend to focus on two science concepts in NRC (2007) report, which are Science concept 3 (Key Planetary Processes Are Manifested in the Diversity of Lunar Crustal Rock), and Science concept 6 (The Moon is an Accessible Laboratory for Studying the Impact Process on Planetary Scales).

Mare Nectaris is a multi-ring impact basin located in the southeast of PKT formed 3.98 ± 0.03 Ga ago. The basin is filled with at least two episodes of mare basalts and distributed with multi-episodes pyroclastic sedimentary rocks and olivine bearing rock outcrops, and possibly possesses the exposure of lunar lower crust or even the mantle materials. These characteristics of Mare Nectaris are helpful to promote the research of key scientific concepts in NRC (2007) report such as: Science goal 3a (Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation), Science goal 3b (Inventory the variety, age, distribution, and origin of lunar rock types), Science goal 3c (Determine the composition of the lower crust and bulk Moon), Science goal 3d (Quantify the local and regional complexity of the current lunar crust), and Science goal 6b (Determine the structure of multi-ring impact basins). In addition, the candidate landing sites could provide support to the astronomical observations and earth plasma investigations on the Moon.

Mare Humorum is a relatively small mare located in the near side of the Moon, which contains high KREEP rocks. Its geological formation process is similar to that of Mare Nectaris but was formed later at about 3.8 Ga–3.9 Ga years ago. Therefore, the key scientific concepts related to Mare Humorum are also similar to those of Mare Nectaris.

Crater Aristillus is located in the east of the Mare Imbrian. It is estimated to have formed in the Copernican period. The oldest geologic unit identified in Crater Aristillus is late Imbrian. The geological age of the crater is relatively young. A central peak and the intrusive dome can be found in Crater Aristillus. Hence, the exploration of this area could possibly

promote the research of key scientific concepts in NRC (2007) report such as Science goal 3d (Quantify the local and regional complexity of the current lunar crust), Science goal 3e (Determine the vertical extent and structure of the megaregolith), and Science goal 6c (Quantify the effects of planetary characteristics such as composition, density, impact velocities on crater formation and morphology).

Crater Kepler is located in the middle east of the Oceanus Procellarum. Three periods of geological units can be identified in this area, which are early Imbrian period, late Imbrian and Eratosthenian. It is estimated that the impact crater was formed in the Copernican period. The research on the key scientific concepts of the Moon that can be promoted by the exploration of this area is similar to that of the Crater Aristillus.

Sinus Iridum is located in the north of the Mare Imbrian with multiple periods of lunar basalt layers distribution, such as the Eratosthenian, Imbrian and etc. The area has a flat terrain which belongs to a typical mare landform (Li et al. 2014). In terms of landform and geological conditions, the Sinus Iridum is a good area for the exploration of lunar surface topography and geological structure.

From above-mentioned description of each landing sites, it is inferred that all the five candidate sites are scientifically rich in specific lunar research fields. The general scientific evaluation scores of Mare Nectaris and Mare Humorum were Excellent, the scores of Sinus Iridum, Crater Aristillus and Crater Kepler were Good (Table 2 in Appendix A).

After that, these candidate landing sites are evaluated and scored by additional scientific and engineering constraints (Appendix A).

We evaluated and scored the five candidates using the factors 1) The demand for Moon based astronomical observation, 2) Topographic slope and Terrain obstacles, 3) Communication ability and 4) Temperature. The final rank order is Sinus Iridium, Crater Aristillus, Mare Humorum, Mare Nectaris, and Crater Kepler (Table 7 in Appendix A). The significant advantages of Sinus Iridum are that it is suitable for Moon based astronomical observation, has a relatively flat terrain, and is good for ground communication and temperature control. Therefore, Sinus Iridum is determined to be the landing site of CE-3 based on the scientific and engineering constraints of CE-3.

To optimize the landing site within the landing area in Sinus Iridum, the control error in the altitude direction would be $\pm 1.5°$ according to the CE-3 spacecraft flight design and the capability of TT&C. Therefore, the range of the landing area should be no less than 3° in the north-south direction. Considering the possibility of in-orbit technical fault, the spacecraft should be able to delay landing for 1 day which may result in the drifting of the spacecraft for about 13° in the longitude direction. Hence, the range of the landing area in the west-east direction should be greater than 13°. Besides, the control error in the longitude direction should also be taken into account (about $\pm 1.7°$). After this optimization, the final landing area is selected to be 18.2° W–34.6° W, 42.6° N–45.6° N within the flat mare area in Sinus Iridum (see Fig. 4).

In the landing site of Sinus Iridum, CE-3 successfully carried out surface topography exploration, geological structure exploration and Moon based astronomical observation obtaining numbers of lunar scientific data (Li et al. 2015). Ling et al. (2015) used the data of Active Particle-induced X-ray Spectrometer (APXS) and Visible and Near Infrared Spectrometer (VNIS) carried by CE-3 probe to derive the chemical composition and mineral abundance of lunar soil and representative mare basalt in the landing area. Their results show that, the lunar basalts near the Guang Han Gong are a new type of lunar basalts with abundant ilmenite and Fe-rich olivine different from the lunar basalts returned from Apollo missions, Luna missions and lunar meteorites. Li et al. (2017), Xiao et al. (2015) analyzed the geologic layer structure of the landing site by using the data obtained by Lunar Penetrating Radar (LPR) carried by Yutu Rover. They analyzed the approximate thickness of the

shallow and deep layers of the lunar surface, and concluded that the geologic unit of this area is relatively young. Wang et al. (2015) analyzed the data obtained by the Moon based Ultra-Violet Telescope (MUVT) and found that an unprecedented upper limit of the content of the OH radicals. The column density and surface concentration of the OH radicals are inferred to be $< 10^{11}$ cm^2 and $< 10^4$ cm^3, respectively. The upper limit of $< 10^4$ cm^3 derived for the OH radicals is lower than that derived from the Hubble Space Telescope (i.e, $< 10^6$ cm^3) by about two orders of magnitude. He et al. (2016) analyzed the data captured by the Moon-based Extreme Ultraviolet Camera (EUVC) onboard CE-3 lander, dedicated to reveal the response of earth's plasmaspheric configuration to substorms. Through these exploration data captured in Sinus Iridum, scientists found a new type of lunar basalt, determined the shallow geological structure in the north of the Mare Imbrium, promoted the research on key scientific concepts such as the types of rocks on the lunar surface, geologic structure, OH/H2O distribution, and etc. The Astronomical and Earth observations were also successfully performed on the lunar surface.

With above mentioned scientific findings of CE-3 mission, it is confirmed that the 3 scientific objectives have been achieved. Moreover, the selected landing site is conducive to the work of CE-3 probe on the lunar surface. Although the rover only traveled about 114 meters due to the technical problem, the CE-3 lander has worked well for a long time, and the working time of the MUVT is far beyond the expectation (the lander and MUVT is still alive). This indicates that the landing site of Sinus Iridum has a good temperature and communication environment for the probe, and thus demonstrates the effectiveness of our selection method.
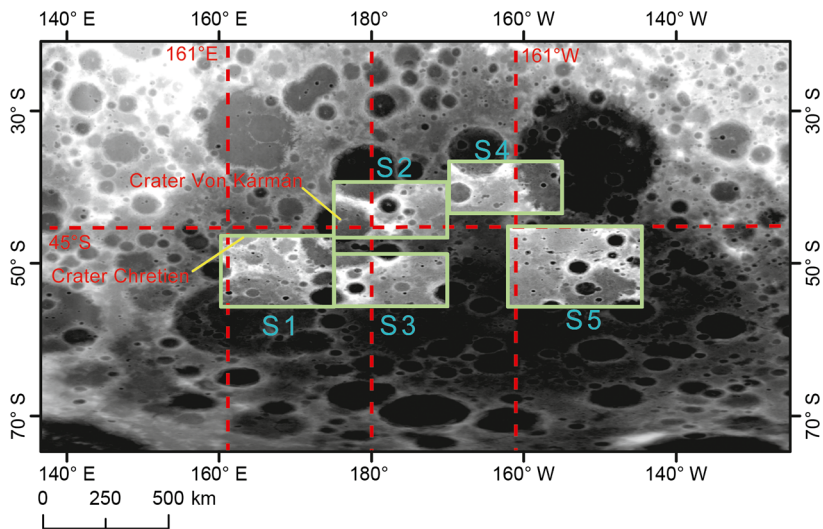
4.2 CE-4 Landing Site Selection

CE-4 is the backup spacecraft of CE-3. Its main scientific objectives are: low-frequency radio astronomy observation in the far side of the Moon, shallow structure detection in the far side of the Moon, and morphology and mineral composition detection of the far side of the Moon. CE-4 has a lander, a rover and a relay satellite, each carrying multiple payloads (Jia et al. 2018).

According to realization of scientific objective and the technical feasibility of CE-4, nine candidate landing areas were initially selected from the lunar far side, four in the northern hemisphere (N1-N4) and five in the southern hemisphere (S1-S5) (Jia et al. 2018). Analysis results show that SPA basin in the southern hemisphere has a low average altitude and relatively large area of flat surface, in which lunar deep material could be possibly found. Therefore, the candidate areas in southern hemisphere have better scientific exploration value, and the S1-S5 in SPA basin is determined as the candidate area. From general scientific aspects ((Jia et al. 2018)), the scientific evaluation score of S5 is Excellent, and the others are Good (Table 8 in Appendix B).

After this preliminary selection, these candidate landing areas are further evaluated and scored by the engineering constraints (Appendix B).

Considering scientific and engineering constraints such as 1) Topographic slope and Terrain obstacles, 2) Communication ability, and 3) Temperature, we evaluated and scored the five candidate areas, and the rank order is S2, S5, S3, S4, S1 (See Table 12 in Appendix B). The significant advantages of S2 are that it is good for communication with relay satellite and has good temperature condition. S5 is a better area from scientific aspect, however, the engineers in CE-4 TT&C group suggested, the relay communication ability could be endangered if the longitude exceed $180° \text{ E} \pm 19°$ (Fig. 5). Therefore, S2 instead of S5 was recognized as a high-priority landing area. In addition, considering the safe landing, the optimized landing area should be a flat area larger than 50 km ∗ 30 km. According to these

Fig. 5 The geo-location of candidate landing areas of CE-4 in the CE-1 topographic map. According to the request of thermal control, the candidates S1-S5 were suggested to be close to the latitude of 45° S, and according to request of the communication ability to relay satellite, candidates were suggested to be within the longitude of 161° E–161° W. According to the request of topographic slope and terrain obstacles, candidates would be suggested to be within the flat floor of craters. Thus, Crater Von Kármán and Crater Chrétien met all the requirements

requirements, the flat floor of Crater Von Kármán (176.4° E–178.8° E, 45° S–46° S) which has an average slope <8° is finally selected as the optimized landing area (Fig. 4 and Fig. 5).

Considering the possibility of in-orbit technical fault, the spacecraft should be able to delay landing for one day. This could lead to the drifting of spacecraft for about 13° in the longitude direction. Therefore, Crater Chrétien (46.1° S, 163.0° E), a crater to the west of Von Kármán and to the north of S1, was selected as an backup landing site. The flat floor of Crater Chrétien (161.9° E–164.5° E, 45.6° S–46.6° S) was selected as the optimized landing area. The specific location information is shown in Fig. 4 and Fig. 5.

CE-4 successfully landed in the main landing site of Crater Von Kármán in the north of SPA basin on January 3, 2019 (Liu et al. 2019; Wu et al. 2019). SPA basin has a diameter of about 2500 km and a depth of about 13 km. It is the largest impact basin on the Moon (Stuart-Alexander 1978; Wilhelms et al. 1987). It is possible that the lunar crust and mantle materials could be excavated by SPA forming event (Melosh et al. 2017). The diameter of Von Kármán is about 186 km, and the depth is about 5 km. It is estimated that the crater was formed in the pre-Nectarian period, with the wall and the bottom covered by the Imbrian geologic units for several times, possessing complex geologic structure characteristics. On the bottom plain of the crater where the landing site is located, it can be seen that most of the areas are mare basalt materials with low reflectance. There are also many impact ejecta of high albedo can be identified within the landing area. Previous studies have shown that compared to typical mare basalt, there are compositional anomalies in the center of SPA basin, which shows an Mg-pyroxene annulus (Pieters et al. 2001), and a unique low-frequency radio space environment in this area (Huang et al. 2018).

The CE-4 mission is still ongoing at present. The VNIS carried by Yutu-2 will focus on the detection of fresh lunar soil at the ruts, loose lunar soil sputtered from the impact crater, and small rocks found at the landing site. Data of multiple exploration points have been

obtained. Recently, Li et al. (2019a) found the presence of low-calcium (ortho) pyroxene and olivine representing materials that may originate from the lunar mantle by using the first two lunar days' VNIS data and high-resolution topographic image data. The LPR carried by Yutu-2 was working during the rover reconnaissance, and the exploration distance of the rover has exceeded 390 m by February 2020. The acquired data can reveal the geologic layer structures of the area (Li et al. 2020), which can advance our understanding of geological evolution history of SPA basin. The antenna of the Low Frequency Spectrometer (LFS) carried on the lander has been launched, and the low-frequency radio detection is being carried out on the far side of the Moon, which is conducive to the lunar radio study of the ionosphere (Wu et al. 2019). The scientific data of CE-4 will is of significant importance in the research of key scientific concepts such as composition of the lunar deep material, the lunar subsurface structure, and geological evolution history of the Moon.

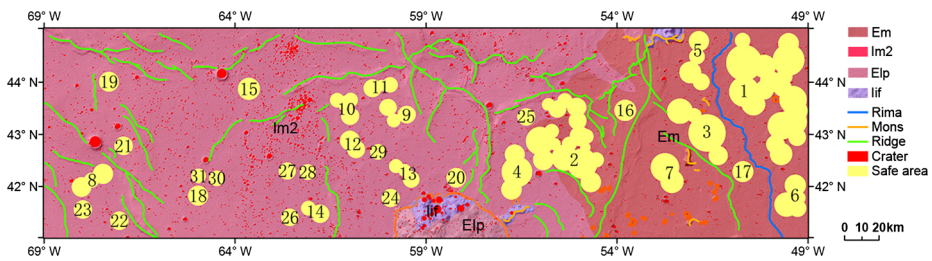### 4.3 CE-5 Landing Site Selection

CE-5 is the first lunar sampling return mission of China. Its main scientific objectives are: in situ investigation and analysis of the landing site; analysis and study of lunar samples (Qian et al. 2018). The acquisitions of lunar samples with relatively young age is highly recommended.

According to the scientific objectives realization and technical feasibility of CE-5, the landing area should be in the lunar near side. Based on the experience of CE-3 landing site selection (Sinus Iridum), the latitude close to 43° (N or S) in the lunar near side is suited for TT&C communication and thermal control. Considering the capability of TT&C of CE-5, the control error in the altitude direction is similar to CE-3 ($\pm 1.5°$). However, since CE-5 mission is more complicated, the range is extended to $\pm 2°$ to improve redundancy. At the same time, considering the spacecraft flight design of CE-5, the spacecraft should be able to delay landing for 3 days, which could result in a drifting of spacecraft for about 20° in the longitude direction. On the basis of these requirements, two areas of $43° \pm 2$ (N or S) and $59° \pm 10°$ W of the lunar near side were initially selected as the candidate landing areas. After that, the two candidate areas in the southern and northern hemispheres are compared and analyzed in terms of their scientific values. Considering that the candidate areas in the northern hemisphere cover the Rümker dome with volcanic geomorphic structures, and the geological age of this area is relatively young, where it might be possible to collect youngest lunar samples. Thus, the northern area has a higher scientific exploration value and was recommended by the lunar experts in CLEP. The final selected landing site is near the Mons Rümker which located in Oceanus Procellarum in the northern hemisphere. The specific geographical location is shown in Fig. 4 (Zeng et al. 2017).

Since the landing area is quite large, to get some high-priority landing sites, we have constrained the regions in a smaller extent within this landing area. Firstly, the terrain obstacles such as Crater, Rima, Ridge and Mons were extracted from the landing area; secondly, 31 safe regions without the terrain obstacles are selected and ordered by their size of area; and thirdly, the geological units layers (Fortezzo et al. 2020) are overlaid to these regions to compare their geologic background. Some of the largest areas in the east side of the CE-5 landing area such as "Area 1", "Area 2" and "Area 3" are in Eratosthenian Mare Unit (Em) (Fig. 6), where it is highly possible to collect younger lunar samples. Therefore, these regions are recommended by the lunar experts as the high-priority landing areas.

It has been found that volcanic dome structure is distributed around the pre-selected landing area of CE-5. The western part of the landing area is in Imbrian period (Im1, Im2 and Im3) with an age of 3.4 Ga–3.5 Ga, which corresponds to the main eruption time of

Fig. 6 High-priority landing areas suggested for CE-5 landing site. Yellow areas marked with number 1–31 are safe areas by avoiding terrain obstacles. Em (dark red area) stands for Eratosthenian Mare Unit, Im2 (light red area) stands for Imbrian Upper Mare Unit, Elp stands for Eratosthenian-Imbrian Plateau Unit and Iif stands for Imbrian Fra Mauro Formation Unit. The largest safe areas in Em Mare Unit such as "Area 1", "Area 2" and "Area 3" have a relatively young geologic age, which are recommended to be the high-priority landing areas

the lunar volcano. While the eastern part is in the younger Eratosthenian period (Em3 and Em4, with an age of <2 Ga), which is almost the youngest lunar mare unit of the lunar surface, and it has never been explored in situ or studied in the laboratory (Qian et al. 2018). If CE-5 spacecraft is able to land and sample the east side, it is likely to obtain rocks related to volcanism or young mare basalts. The collected samples may be different in the age from Apollo and Luna samples, and may be used to revise the existing calibration curve of lunar cratering. The research on the landing site could have a great promoting effect to the study on key scientific concepts such as lunar geologic dating, volcanic activity and thermodynamic evolution.

5 Summary and Prospect

Lunar landing missions (including sampling return) are important to solve some key scientific concepts of the Moon, and the landing site selection is an essential work for the mission. However, the study of some core lunar science goals could not be fully filled at present due to the limited spatial distribution of the available landing sites such as 1) There were too few landing sites in the lunar far side; 2) No landing sites are located at the high latitudes; 3) Lunar samples with specific type of mare rocks are still not available; 4) Lunar samples with relative young age are still not available. For the purpose of promoting the research on such lunar key science concepts, this paper introduces the landing site selection of CE series missions including the general selection principles, process, method and result of the selection. We analyzes the characteristics of the CE-3, CE-4 and CE-5 landing sites, introduces the achievements of CE-3 and CE-4, and forecasts the possible achievements of CE-4 and CE-5 in the future. In summary, all the CE lunar landing sites are designed to expand the spatial limitation of available landing sites, which could help to the study of some science goals of the Moon as mentioned in NRC report (NRC 2007). For example, CE-3 landing site is good for studying new type of lunar mare rocks. CE-4 landing site is designed for the lunar far side study. CE-5 landing site is designed for capturing young lunar samples. The specific corresponding relationship is shown in Table 1.

In future lunar exploration mission, CLEP has set three main scientific objectives, which are: 1) comprehensive research of lunar general science issues; 2) lunar based observation and experimental research; 3) lunar resources in situ utilization test. In order to achieve these scientific goals, China's follow-up lunar exploration initially planned CE-6, CE-7, CE-8 and

Table 1 Key lunar science goals that may be promoted by the study on CE landing sites

Missions	Achieved/Possible research findings	Corresponding science goals
CE-3	By the analysis of the data captured by LPR on Yutu Rover, the subsurface structure of Sinus Iridum in the north of Mare Imbrian is analyzed, and the thickness of the shallow and deep layers is estimated. Which shows that this area may be a geologic unit with relatively young geological age	Science goal 2a: Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales
	By the analysis of the data captured by VNIS on Yutu Rover, a new type of lunar basalt near Gang Han Gong was found	Science goal 3d: Quantify the local and regional complexity of the current lunar crust
	By the analysis of the data captured by MUVT on Lander, an unprecedented upper limit of the content of the OH radicals was found	Science goal 8d: Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps
CE-4	By the analysis of the data captured by LPR on Yutu-2 Rover, The subsurface structure in Von Kármán of the lunar farside is revealed	Science goal 2a: Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales
	By the analysis of the data captured by VNIS on Yutu-2 Rover, the low-calcium (ortho)pyroxene and olivine, materials that may originate from the lunar mantle were found	Science goal 3c: Determine the composition of the lower crust and bulk Moon
	The LFRS is working on the Moon, through the analysis of the captured data, the ionosphere distribution of the Moon would possibly be revealed	Science goal 8b: Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.
CE-5	Through sampling and return exploration, it is possible to obtain the youngest mare basalts, so as to accurately measure the age of the young basalts, and build a more accurate calibration curve of the crater dating	Science goal 1c: Establish a precise absolute chronology Science goal 5b: Determine the age of the youngest and oldest mare basalts

other follow-up lunar exploration missions (Li et al. 2019b). The corresponding landing site selection work has also been carried out at the same time. In accordance with the scientific concepts concerned by the CLEP (e.g. the distribution of water and ice on the Moon, the inner structure and formation process of the Moon, the heterogeneity of the inner material of the Moon, the evolution of the energy and material inside the Moon (Ouyang et al. 2005)), high altitude areas in south pole region are inclined to be selected as the new landing sites (Li et al. 2019b).

The selection of China's lunar landing site is the result of a trade-off between the constraints of scientific goals and engineering conditions. In the landing site selection for early CE mission, more attention is paid to ensure the safety of the spacecraft. With the progress of lunar and deep space exploration technology in China, the requirement of scientific goals will play an increasingly important role in the selection of future landing sites. Under this trend, the landing sites selected for CLEP switch from the lunar near side to the lunar far side; from the flat lunar mare to the boundaries of the lunar mare and highlands, and to the more complex lunar highland area; from the middle and low latitudes to the polar re-

gions of the Moon. The landing environment have developed from simple flat lunar mare to more complex landing sites that will yield high scientific returns which include magnetic anomalies with swirls, pit crater/lava tubes, pyroclastic deposit and domes. In future, we will focus on the long-term goal of "establishing an unmanned research station on the Moon", selecting candidate lunar landing areas to meet scientific goals and engineering needs, and providing more exploration data and samples for lunar scientific research community around the world.

Conflict of interest   We declare that we do not have any conflict of interest in connection with the manuscript submitted.

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Appendix A: Evaluation of CE-3 Candidate Landing Areas

A.1 General Scientific Evaluation

From above description of each landing sites, it is inferred that all the five candidate sites are scientifically rich in specific lunar research fields. Since the Mare Nectaris and Mare Humorum are thought to be distributed with olivine bearing rock outcrops, which are suggested by the lunar experts in CLEP. Then from the general scientific aspect, Candidates with more scientific goals and research interests will get a better score, see Table 2.

Table 2 General scientific evaluation result of CE-3 candidate landing areas

Name	Scientific characteristics	Evaluation result
Mare Nectaris	Science goal 3b, 3c, 3d, 6b	Excellent
Mare Humorum	Science goal 3b, 3c, 3d, 6b	Excellent
Sinus Iridum	Science goal 2a, 3d, 8d	Good
Crater Aristillus	Science goal 3d, 3e, 6c	Good
Crater Kepler	Science goal 3d, 3e, 6c	Good

Table 3 Evaluation result based on the demand of Moon based astronomical observation

Name	Geo-location	Evaluation result
Sinus Iridum	44.1° N, 31.5° W	Excellent
Crater Aristillus	33.9° N, 1.2° E	Good
Crater Kepler	8.1° N, 38.0° W	Fair
Mare Nectaris	15.2° S, 35.5° E	Poor
Mare Humorum	24.4° S, 38.6° W	Poor

Table 4 Evaluation result based on topographic and terrain obstacles

Name	Average slope	Percentage of area (Slope < 8°)	Average waviness	Evaluation result
Crater Kepler	2.33°	96.88%	50.72 m	Excellent
Sinus Iridum	2.85°	91.97%	62.37 m	Excellent
Crater Aristillus	3.62°	89.37%	79.70 m	Good
Mare Humorum	4.16°	85.48%	91.60 m	Good
Mare Nectaris	5.05°	80.09%	112.13 m	Good

A.2 Evaluation with Scientific and Engineering Constraints

A.2.1 The Demand of Moon Based Astronomical Observation

The principle investigator of MUVT provided some suggestions to evaluate the landing sites. Firstly, since the observation equipments in China are all in the northern hemisphere of the Earth, in order to facilitate simultaneous observation, the location of the MUVT also needs to be in the northern hemisphere of the Moon. Secondly, higher latitudes are recommended where the SEA will be relatively smaller, and then the stray light influence will be relatively less, which is better for the observation of MUVT. Candidates with geo-location in the northern hemisphere, and in relative high latitude will get a better score, see Table 3.

A.2.2 Topographic Slope and Terrain Obstacles

We calculated the average slope, the area proportion of slope less than 8°, and average waviness of these landing sites using CE-1 DEM data (Li et al. 2014), calculated with a baseline of 1.5 km, all the average slope is smaller than 8° which would meet the requirement. Candidates with relative low average slope, small average waviness and has larger area of slope <8° will get a better score, see Table 4.

A.2.3 Communication Ability

Since the proposed landing sites are in the lunar near side, then the TT&C observation time of them could meet the requirements, so that, we just evaluated the communication ability by the antenna rotate angle of the ground station. The proposed landing site which leads to a small antenna rotate angle means the communication is more convenient. Thus, Candidates with relative small range of Azimuth angle, Inclination Angle and Angular area will get a better score, see Table 5.

A.2.4 Temperature

According to the constraint, the landing site which altitude is suggested to be 30°–60° (N or S). Candidates with latitude close to 45° (N or S) will get a better score, see Table 6.

Table 5 Evaluation result based on communication ability

Name	Azimuth angle range	Inclination angle range	Angular area	Evaluation result
Sinus Iridum	301.52°–322.09°	32.28°–43.95°	20.57° * 11.67°	Excellent
Mare Humorum	19.90°–35.97°	36.67°–53.11°	16.07° * 16.44°	Excellent
Mare Nectaris	145.82°–171.39°	45.29°–56.91°	25.57° * 11.62°	Good
Crater Kepler	178.11°–199.03°	43.50°–58.57°	20.92° * 15.07°	Good
Crater Aristillus	255.77°–281.11°	49.29°–63.64°	25.34° * 14.35°	Fair

Table 6 Evaluation result based on temperature requirement

Name	Geo-location	Evaluation result
Sinus Iridum	44.1° N, 31.5° W	Excellent
Crater Aristillus	33.9° N, 1.2° E	Good
Crater Kepler	8.1° N, 38.0° W	Poor
Mare Nectaris	15.2° S, 35.5° E	Poor
Mare Humorum	24.4° S, 38.6° W	Poor

A.3 Evaluation Result

With above factors, the evaluation results are shown as Table 7.

In Table 7, the scores for Excellent, Good, Fair and Poor are 3, 2, 1 and 0, and if the total score of two candidates are the same, then we would consider the weight of the factors, the order of the weight for factors in the table is "Scientific evaluation > I1 > I3 > I2 > I4".

Appendix B: Evaluation of CE-4 Candidate Landing Areas

B.4 General Scientific Evaluation

Considering the lunar experts in CLEP suggestion, all the candidates in SPA basin are nice. The materials in the region are rich in mafic, which are likely to be of great significance to reveal the compositions of the crust and even the mantle of the Moon (Pieters et al. 2001).

Nectarian plain is the main base material of S5 exposed area with several ancient craters formed in Nectarian era or pre-Nectarian era (Wilhelms et al. 1987). So, S5 was given a better score which are suggested by the lunar experts in CLEP, see Table 8.

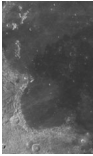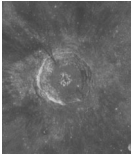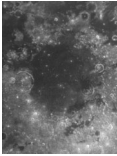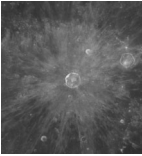### B.5 Evaluation with Scientific and Engineering Constraints

B.5.5 Topographic Slope and Terrain Obstacles

We calculated the average slope, the area proportion of slope less than 8°, and average waviness of these landing sites using CE-1 DEM data (Li et al. 2014), calculated with a baseline of 1.5 km, all the average slope is smaller than 8° which could meet the requirement. Candidates with relative low average slope, small average waviness and has larger area of slope <8° will get a better score, see Table 9.

B.5.6 Communication Ability

Since CE-4 is a lunar far side landing mission, the communication ability is up to the relative position of the landing site to the relay satellite, which is different from CE-3 mission.

Table 7 The geo-location and evaluation of the proposed landing sites for CE-3

Name	Map	Latitude	Longitude	Scientific evaluation	I1	I2	I3	I4	Rank
Sinus Iridum		44.1° N	31.5° W	Good	Excellent	Excellent	Excellent	Excellent	1
Crater Aristillus		33.9° N	1.2° E	Good	Good	Good	Fair	Good	2
Mare Humorum		24.4° S	38.6° W	Excellent	Poor	Good	Excellent	Poor	3
Crater Kepler		8.1° N	38.0° W	Good	Fair	Excellent	Good	Poor	4
Mare Nectaris		15.2° S	35.5° E	Excellent	Poor	Good	Good	Poor	5

Table 8 General scientific evaluation result of CE-4 candidate landing areas

Name	Scientific characteristics	Evaluation result
S5	In SPA, Science goal 2a, 3c, 8b	Excellent
S1	In SPA, Science goal 2a, 3c, 8b	Good
S2	In SPA, Science goal 2a, 3c, 8b	Good
S3	In SPA, Science goal 2a, 3c, 8b	Good
S4	In SPA, Science goal 2a, 3c, 8b	Good

Table 9 Evaluation result based on topographic and terrain obstacles

Name	Average slope	Percentage of area (Slope $<8°$)	Average waviness	Evaluation result
S4	4.74°	81.77%	106.16 m	Excellent
S5	4.92°	81.53%	110.45 m	Excellent
S1	5.05°	79.73%	110.18 m	Good
S3	5.36°	78.74%	118.82 m	Good
S2	5.91°	73.79%	131.71 m	Good

Table 10 Evaluation result based on communication ability

Name	Geo-location	Evaluation result
S2	39° S–46° S, 175° E–170° W	Excellent
S3	48° S–55° S, 175° E–170° W	Excellent
S1	46° S–55° S, 160° E–175° E	Good
S4	36° S–43° S, 170° W–155° W	Good
S5	45° S–55° S, 162° W–144° W	Fair

Table 11 Evaluation result based on temperature requirement

Name	Geo-location	Evaluation result
S2	39° S–46° S, 175° E–170° W	Excellent
S5	45° S–55° S, 162° W–144° W	Good
S1	46° S–55° S, 160° E–175° E	Good
S4	36° S–43° S, 170° W–155° W	Good
S3	48° S–55° S, 175° E–170° W	Good

Thus the method to evaluation this factor is different from CE-3, and the engineers of the relay satellite request the landing site to be close to the longitude 180° E. Candidates with longitude close to 180° E will get a better score, see Table 10.
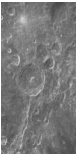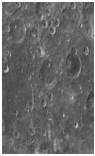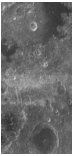
B.5.7 Temperature

According to the constraint, the landing site which altitude is suggested to be 30°–60° (N or S). Candidates with latitude close to 45° (N or S) will get a better score, see Table 11.

B.6 Evaluation Result

With above factors, the evaluation results are shown as Table 12.

In Table 12, the scores for Excellent, Good, Fair and Poor are 3, 2, 1 and 0, and if the total score of two candidates are the same, then we would consider the weight of the factors, the order of the weight for factors in the table is "Scientific evaluation > I2 > I1 > I3".

Table 12 The geo-location and evaluation of the proposed landing sites for CE-4

Name	Map	Latitude	Longitude	Scientific evaluation	I1	I2	I3	Rank
S2		39° S–46° S	175° E–170° W	Good	Good	Excellent	Excellent	1
S5		45° S–55° S	162° W–144° W	Excellent	Excellent	Fair	Good	2
S3		48° S–55° S	175° E–170° W	Good	Good	Excellent	Good	3
S4		36° S–43° S	170° W–155° W	Good	Excellent	Good	Good	4
S1		46° S–55° S	160° E–175° E	Good	Good	Good	Good	5

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