Real-time and High-Accuracy VLBI in the CE-3 Mission

Weimin Zheng[1,2], Yong Huang[1], Zhong Chen[1,2], Guangli Wang[1,2], Qinghui Liu[1,2], Fengxian Tong[1], Peijia Li[1], Li Tong[1], Fengchun Shu[1,2]

Abstract On 14 December 2013, the Chang'E-3 (CE-3) lunar probe successfully landed on the Moon and then released the Yutu rover. To support this mission, the Chinese VLBI Network (CVN) made important upgrades: the new VLBI Center and the 65-m Tianma antenna were built in Sheshan on the periphery of Shanghai. To get high-precision delay results, the beacon onboard the CE-3 probe was designed to emit a set of special X-band Differential One-way Range (DOR) signals. The CVN used the real-time ΔDOR technique to track the lander and to eliminate systematic errors as much as possible. During the circum-lunar orbit, the VLBI delay residuals after orbit determination were $\sim$0.5 ns (using a 5-second integration time). The absolute position accuracy of the lander using the VLBI group delay is approximately 100 meters. The e-VLBI technique reduced the turnover time for the observations to $\sim$15–45 seconds. After landing, using the same-beam VLBI mode, the phase delay and phase reference mapping methods were used to determine the relative position of Yutu reaching an accuracy of 1 meter. The real-time and high-accuracy VLBI data greatly supported the CE-3 mission.

Keywords Real-time VLBI, lunar exploration, Delta-DOR, phase reference mapping, lunar surface positioning, orbit determination

1. Shanghai Astronomical Observatory, Chinese Academy of Sciences
2. Key Laboratory of Radio Astronomy, Chinese Academy of Sciences

1 Introduction

Chang'E-3 (CE-3) is China's first soft-landing and roving exploration on the Moon. It is also the first probe to soft-land on the Moon since Luna 24 in 1976. The mission objective is to demonstrate and develop key technologies for future lunar and deep-space exploration missions. The scientific objectives include the exploration of the lunar surface topography, a lunar surface material composition and resource survey, and the realization of lunar-based astronomical observations.

The CE-3 spacecraft was launched on 2 December 2013. It entered a 100-km-high polar orbit on 6 December, then adjusted to an elliptical orbit of 15×100 km, and finally realized a soft-landing on the Moon. CE-3 deployed the Yutu (Jade Rabbit) rover on 14 December 2013. The success of the CE-3 mission marks the transition of the Chinese Lunar Exploration Program from the first phase of orbital missions to the second phase of soft-landing. As the first soft-landing on the Moon since the Apollo missions, it is also one of the most complicated space exploration missions China has undertaken so far. To guarantee the high accuracy and high reliability, many new facilities and techniques were used for the first time.

The CE-3 mission used a combination of the Chinese space flight telemetry, tracking, and command (TT&C) network, the Chinese VLBI Network (CVN), and some ESA stations to compose the complex TT&C system [1]. Before the mission, the new Kashgar and Jiamusi deep-space stations joined the China TT&C network. Almost at the same time the Tianma 65-m antenna and the new VLBI Data Center of the CVN were put into operation.

There were five operation phases in the mission: the launch phase, the Earth-Moon transfer orbit phase,

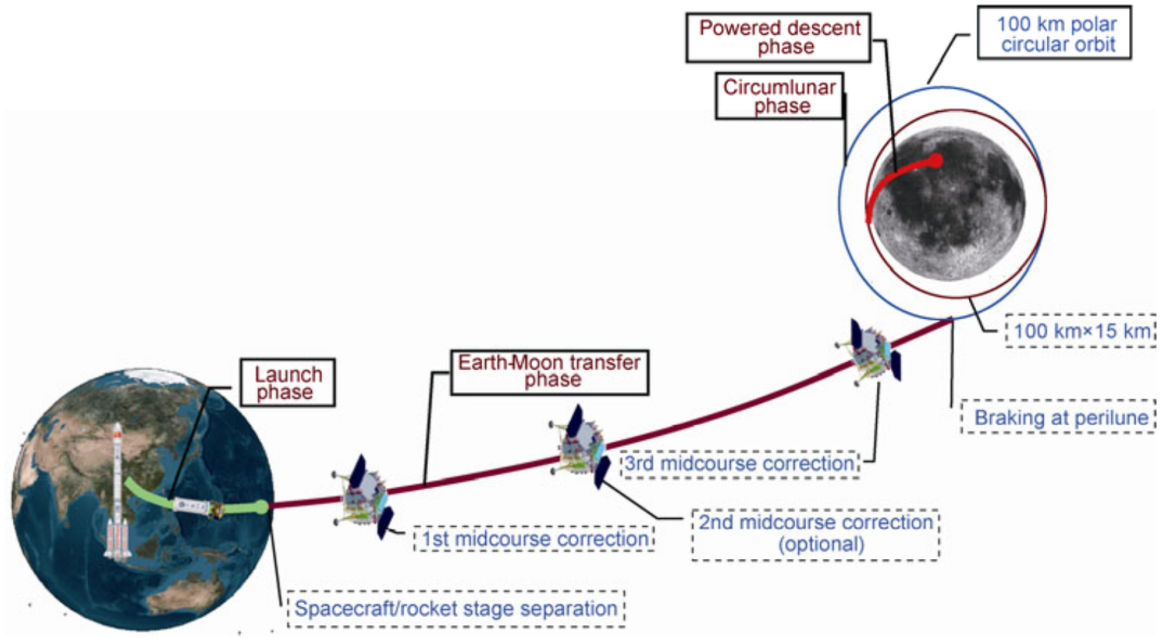

Fig. 1 CE-3 main trajectory (from Xinhua news agency).

the circum-lunar phase, the powered descent phase, and the lunar surface work phase. The TT&C working frequency changed from S-band to X-band with the Earth–Moon transfer phase. Shanghai station (including Tianma & Sheshan), Beijing station, Urumchi station, Kunming station, and the new CVN Data Center took part in tracking the probe from the Earth–Moon transfer phase to the power descent phase to the lunar surface working phase (Figure 1). The planned third mid-course correction (Trajectory Correction Maneuver, TCM-3) was canceled because of the high accuracy tracking.

Many new techniques and facilities improved the performance of the CVN. For using the real-time X-band Differential One-way Range (ΔDOR), the VLBI group delay was less than 0.5 ns (using a 5-second integration time), which is ten times better than that of the CE-1 mission. The total data turnaround time of the whole CVN system is shorter than one minute. The real-time performance of data transmission and processing featured tenfold increases, playing an irreplaceable role in time critical and important situations such as two mid-course corrections or Trajectory Course Maneuvers (TCMs), the braking of the Lunar Orbit Insertion (LOI), the powered descent, and the soft-landing. After landing, VLBI and three-way range data were used to determine the lander position to better than 100 meters. After the critical mission, using of the same-beam VLBI observation data, the relative position of Yutu to the lander was improved to about 1 meter by VLBI phase delay and phase reference mapping techniques.

2 CVN Status in the CE-3 Mission

According to the requirements of the TT&C system, the CVN should carry out the probe tracking and orbit/position determination. In the Earth–Moon transfer orbit phase and the circum-lunar phase, the CVN had to complete ΔDOR tracking, orbit/angular position determination, and orbit prediction. In the lunar surface phase, the CVN should complete lander and rover same-beam VLBI tracking, the lander 3D positioning, and the rover positioning relative to the lander. These are new tasks; for this reason, we have completed the station and Data Center upgrade before the mission.

The CVN consists of five stations and one Data Center (Figure 2). After the first construction stage of the Shanghai Tianma 65-meter antenna was completed, the antenna was equipped with an S/X-band observation system. The other four stations are Beijing Miyun (50-m), Urumchi Nanshan (25-m), Yunnan Kunming (40-m), and Shanghai Sheshan (25-m). The baseline Shanghai–Urumchi is the longest baseline with a length of 3,200 km.

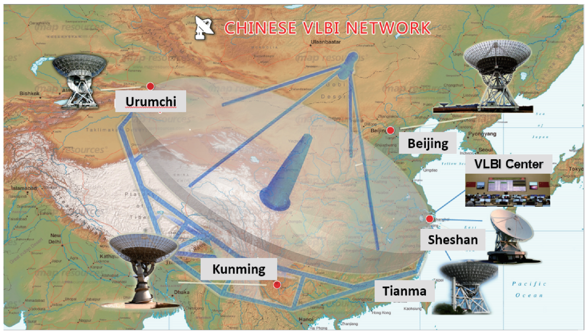

Fig. 2 CVN configuration of five antennas and one Data Center in the CE-3 mission.

In order to improve the reliability, redundant designs were carried out in various aspects, such as the system design, the station observation system, the network system, and the data center.

Although three stations are the minimum configuration for CE-3 VLBI tracking, there are actually five stations. The strategy is to make sure three of four stations are always available during the critical mission period. There are two antennas at Shanghai station. The Tianma antenna is the main antenna and the Sheshan antenna is the backup antenna. The big Tianma antenna not only strengthens the CVN signal reception capacity, it also improves the reliability of Shanghai station. In the critical mission phase, the Tianma and Sheshan antennas tracked the CE-3 probe and sent the data to the VLBI Center simultaneously. But in the VLBI Center only data from Tianma were correlated, while data from the Sheshan antenna were just received and stored for offline data processing.

Before the mission, the new VLBI Data Center was successfully completed in the Sheshan park of Shanghai Astronomical Observatory (SHAO). The VLBI Center has eleven configuration items: e-VLBI data transfer, schedule, software correlator, hardware correlator, station monitoring, media error correction, group delay, phase delay, orbit determination, position determination, and system operation and management. To enhance reliability, there are two data pipelines. The one headed by the software correlator is the main pipeline, the one headed by the hardware correlator is the backup. The software correlator adopts parallel algorithm and runs on a set of blade-based clusters; the hardware correlator adopts FPGA technology. For the same reason, all operation positions have backups.

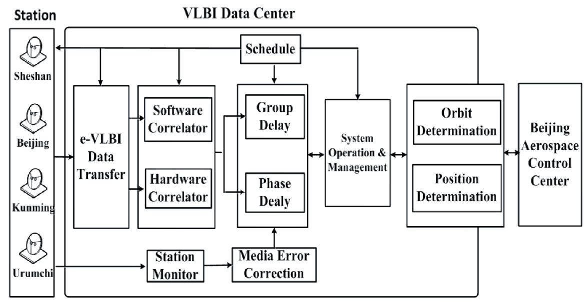

Fig. 3 CVN Data Center configuration.

3 New Techniques Improve the Orbit Determination and Position Accuracy

The techniques like real-time ΔDOR, same-beam lander and rover positioning were first used with the CE-3 mission (Table 1).

Table 1 Technique and device improvements of the CE-3 mission with respect to the CE-1/2 missions.

	CE-3	CE-2	CE-1
ΔDOR technique	First use	experiment	/
Same beam VLBI	First use	experiment	/
e-VLBI data rate	64 Mbps	32 Mbps or 16 Mbps	16 Mbps or 8 Mbps
Data Acquisition system	CDAS	CADS	ABBC
Station	5	4	4
VLBI Data center	Sheshan	Xu Jiahui	Xu Jiahui
Rover & lander positioning	First use	/	/
Noise level (5-second integration time)	$<$0.5 ns	$\sim$4–5 ns	$<$5.5 ns

3.1 *Real-time X-band ΔDOR*

The real-time X-band ΔDOR tracking technique was applied for the first time in CE-3. A special DOR beacon onboard the CE-3 probe substituted the S-band beacon used in CE-1/2. The DOR beacon emits two pairs of tones with higher onboard efficiency than the normal band limited continuous spectrum signals (Figure 4).

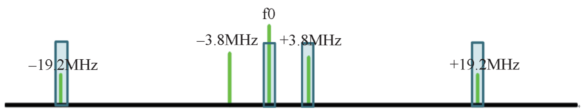

Fig. 4 Spectrum of X-band CE-3 DOR signal. Three tones and the carrier are recorded.

The carrier is denoted by f0. The second (lower-frequency) DOR tone is ±3.8 MHz, which is used to resolve phase ambiguity. The first (high-frequency) DOR tone is ±19.2 MHz, which determines the group delay accuracy [2]. Using the multiple signal synthesis technique, the measurement-limiting errors are inversely proportional to the spanned bandwidth of 38.4 MHz.

The CE-3 probe emitted two sets of carrier and DOR signals (one as backup). For each set of signals, the carrier, the upper second DOR tone, and the two first DOR tones were recorded in four channels. Hence, two pairs of DOR signals were recorded in eight BBC channels with 2 MHz bandwidth and 2-bit resolution. The total data rate per station thus amounts to $2 \times 4\,\mathrm{CH} \times 4\,\mathrm{MHz/CH} \times 2\,\mathrm{bit} = 64$ Mbps.

The frequency shift to X-band greatly reduces the ionosphere correction error (to a sixteenth part) compared to the S-band tracking system. To minimize the common-mode errors that arise from uncertainty in media delays, clock offsets, instrumental delays, and station locations, the differential measurement named ΔDOR was adopted [3]. The quasars with a small angular separation from the CE-3 spacecraft were the references. The scan sequence is Quasar–CE-3–Quasar–CE-3 with a switching interval of five minutes. The angular distance between CE-3 and the quasar is less than 10°. The big Tianma antenna was beneficial for quasar observations and improved the VLBI measurement accuracy.

The ΔDOR technique greatly improved the VLBI data accuracy. The formal error of the VLBI group delay was less than 0.2 ns. The delay residuals were at a level of 1 ns in trans-lunar orbit and decreased to a level of 0.5 ns in lunar orbit (Figure 5).

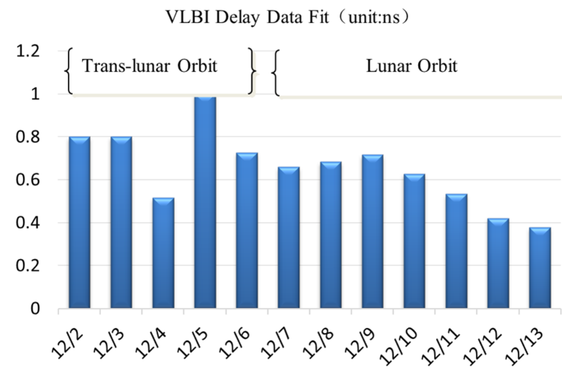

Fig. 5 Group delay residuals decreased to a level 0.5ns in the lunar orbit.

A ΔDOR test experiment had been run in the CE-2 mission. At that time, the data were correlated in the post-processing mode. But in the CE-3 mission, the CVN worked in real-time mode during the critical period from 2–20 December 2013. The planned total VLBI data turnaround time should be less than one minute, compared to ten minutes turnaround time in CE-1 and CE-2. This was a considerable challenge for the whole system.

Real-time e-VLBI is the fundamental technique. It consists of a station data transmitting unit, the Data Center receiving and distributing unit, and a Wide Area Network (WAN) link. The station data transmission unit is based on the Mark 5B+ system with specifically designed software to gather data from the CDAS digital terminal and to send data through a dedicated network. At the VLBI Center, the data servers received and distributed raw VLBI data to the software and hardware correlators in parallel. The raw data were stored on local disk arrays at the same time.

Each station had main and spare dedicated WAN fiber links to the VLBI Center protected by Border Gateway Protocol (BGP) for data transmission. There was a network management system to monitor the network status. If any one of the main lines was under unstable condition, it would switch to the backup line automatically. The switch time is shorter than 1 second to minimize the impact on the real-time data transmission.

In the VLBI Center, specific modules for e-VLBI data transfer, correlator, group delay, position determination, and system operation and management were designed to improve the real-time capability. They

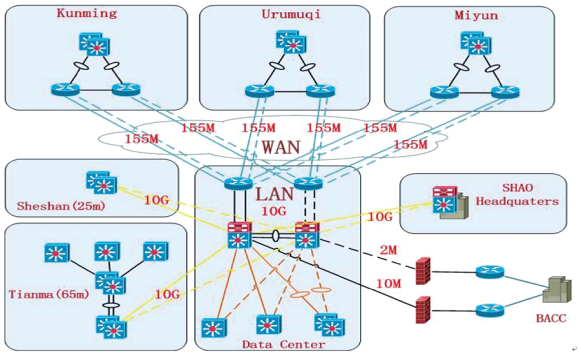

Fig. 6 CVN network with dual path connection.

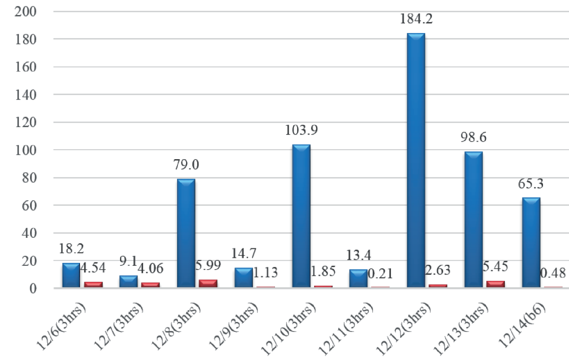

Fig. 7 POD of Lunar Orbit Compared with BACC(unit:m).

worked in pipeline mode. The intermediate data were exchanged through the Network File System (NFS) at a fixed rate. During the critical mission the shortest turnover time, from receiving the signal to producing the CE-3 angular position, was 25 seconds. In the special orbit maneuver procedure, when the software opened the onsite fringe search and delay model reconstruction function, the turnover time rose to 40 s.

3.2 High Accuracy VLBI Data Improve the Orbit Determination Results

In the CE-3 mission, the new facilities and techniques of the Chinese deep-space stations and the CVN improve the tracking capability of the range and delay data to a level of better than 1 m and 1 ns, respectively. The analysis reveals that the high eccentricity character of the trans-lunar orbit is not good for Precision Orbit Determination (POD) and that the orbit accuracy decreases as the probe flies away from the Earth. However, combining the VLBI data greatly improves the accuracy of the short arc orbit determination as compared to the result of using range data only in each phase of the mission. The orbit differences between the solutions from SHAO and Beijing Aerospace Control Center (BACC) in three dimensions are at the level of 1 km and 100 m in trans-lunar orbit and lunar orbit, respectively (Figure 7).

The strategy of estimating the empirical accelerations in the POD helps to reduce the impact of attitude control in the CE-3 mission. For 100×100 km and 100×15 km lunar orbits, the total position consistency is found to be at the level of 20 m (3 m in the radial direction) and 30 m (4 m in the radial direction), respectively. These are better than those for CE-2, which are at a level of 30 m (5 m in the radial direction) and 46 m (12 m in the radial direction) respectively; and they are much better than those for CE-1 with several hundreds of meters. The orbit accuracy of the CE-3 probe is at the same level as other contemporary lunar probes such as SELENE and LRO. The position error of the soft-landing trajectory is less than 100 m based on the kinematic POD method.

3.3 Lander and Rover Positioning

Because of the impact of range biases, the accuracy of the soft-landing trajectory and position of the lander with the range data only is up to a level of several km. However, VLBI data can improve the lander position accuracy to a level better than 100 m, and the relative position of the Yutu rover to the lander to a level of 1 m.

In the CE-3 mission, one of the important tasks of the CVN is to determine the locations of the lander and the rover. For the lander positioning task VLBI and range data were used; for the relative positioning of the rover to the lander same-beam VLBI was used.

The onboard range and DOR beacons were shut down about one hour after the soft landing. The lander directional antenna only transmitted wideband scientific data; the rover transmitted wideband scientific data through the directional antenna or transmitted narrowband telemetry signals through the omni-directional antenna according to the operational program. To avoid interrupting scientific data transmission, CVN stopped observing extragalactic radio sources after landing. So we only used the effective one-hour, three-way range and VLBI measurements to determine the lander position in the lunar body-fixed coordinate system. The conversion from the principal axes to mean axes is given by DE421. The lander position is in Table 2.

Table 2 Comparison of the lander locations determined by CVN and NASA.

	Latitude	Longitude	Height
CVN	44.1206°	−19.5124°	−2632.0 m
NASA	44.1214°	−19.5116°	−2640.0 m
Difference	24 m	17 m	4 m

In order to evaluate the position accuracy of the lander, the NASA Lunar Reconnaissance Orbiter (LRO) Digital Elevation Model (DEM), a spherical harmonic model of degree and order 2050 was used. The DEM spatial resolution is about 2.66 km. We input the lander longitude and latitude from the CVN into the DEM and got the elevation of −2636 m. On 25 December, LRO flew over the lander site and NASA published a lander position based on the images taken by the LRO camera [4]. The total difference of the CVN and LRO locations is less than 50 m.

On 15 December, the lander commenced deploying the Yutu rover. Yutu moved around the lander and they photographed each other at the parking positions A, B, C, D, and E. The CVN used same-beam VLBI to locate Yutu's relative position to the lander. The coordinates that describe the relative position between the lander and the rover are defined in the lander-centered NEG (North East Ground) coordinate system. The x-axis is pointing to the north, the y-axis is pointing to the east in the horizontal plane, and the z-axis is perpendicular to the x-axis and the y-axis, constructing a right-handed system [1].

VLBI observations were used to determine Yutu's relative position. During the mission, the relative position was calculated from the differential group delay and reached the 100-m level. After the critical mission, the differential phase delay as well as the phase-referencing mapping method were used; this greatly improved the position accuracy. The group delay noise was at the level of several ns, and that of phase delay was at the level of 1 ps with an ambiguity at a level of ns.

When utilizing phase delay data to determine the relative position, phase ambiguities for each baseline need to be solved. We solved for a VLBI phase delay bias for each baseline in relative positioning. Because the rover was close to the lander and the terrain at this location was relatively flat, we fixed the prior elevation parameter of the rover and set it the same as that of the lander.

In addition, the same-beam phase-referencing mapping method was adopted to obtain an accurate relative position for Yutu. Firstly, the software correlator output visibilities were converted to the uniformed FITS-IDI format, and then AIPS and Difmap, the astronomical mapping softwares, were utilized to complete the mapping and angular positioning of the Yutu antenna (Figure 8). A new positioning algorithm was developed to determine the rover lunar positions. We took advantage of same-beam observations with the signals of the lander and the rover being received in the same digital terminal to eliminate system errors.

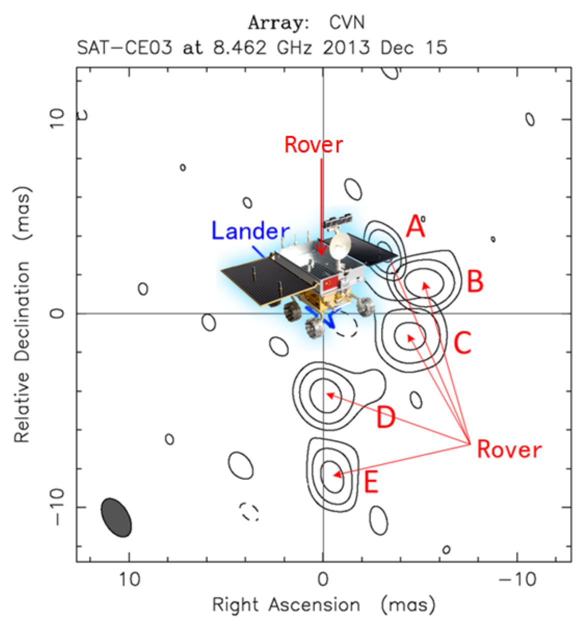

Fig. 8 Five rover positions with respect to the lander by a same-beam phase-referencing map.

The three VLBI relative positions from the group delay, phase delay, and VLBI map are compared with the results from the visual localization by the onboard Stereo Cameras (Table 3). The position differences are at a magnitude of hundreds of meters for the group delay data but decrease to about 1 m for phase delay and phase-referencing map data. Systematic errors in the differential group delay degrade the accuracy of the relative position, especially at point B. At that time, there were only about ten minutes of data from three antennas (Beijing, Kunming, and Tianma).

Table 3 Three VLBI relative position results compared with those from visual localization (unit: m).

Site		Visual	Group delay	Phase delay	Phase-referencing map
A	N	9.03	−4.2	11.25	9.47
	E	1.50	0.4	1.28	1.15
B	N	5.00	−269.8	5.89	5.12
	E	8.90	−640.8	7.56	9.30
C	N	−5.65	80.5	−4.92	−5.34
	E	8.36	10.0	8.02	8.86
D	N	−9.75	112.6	−8.73	9.51
	E	0.27	69.2	0.37	0.49
E	N	−19.76	59.0	−17.35	−19.26
	E	−0.20	32.0	−0.42	−0.29

Considering that the accuracy of the relative positions based on the visual localization method is about 4% of the distance between the lander and the rover, the position accuracy for the phase delay and phase-referencing map results can reach the 1-m level [5].

4 Conclusions

CE-3 is the first Chinese lunar probe that soft-landed on the surface of the Moon. Real-time and high accuracy VLBI has played a very important role in this mission. ΔDOR can improve the orbit determination and prediction accuracy remarkably, especially in the critical sections like TCM, LOI braking phase, or powered descent phase. Using VLBI and range data, the lander position can be better than 100 m. The relative position accuracy determined by same-beam VLBI is about one meter. Real-time ΔDOR and same-beam VLBI are anticipated to be used in the CE-5 rendezvous and docking mission as well as in other planetary exploration missions of China.

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