The LUNAR ORBIT PHASING AND RENDEZVOUS TESTS OF CHANG'E-5 REENTRY FLIGHT EXPERIMENT VEHICLE

Gefei Li, Jianfeng Xie, Jianliang Zhou, Jun Song
Beijing Aerospace Control Center, POB.5130, NO.105, Beijing, China, 100092
sophiebacc@sina.com

Abstract: *Chang'e-5 is China's first lunar sample return probe and Chang'e-5 reentry flight experiment (CE-5T1) is a flight test for Chang'e-5 mission which vehicle was launched in October 24th 2014. After the return capsule of CE-5T1 separated from the service module and landed on the earth smoothly, the service module has continued to execute a series of expanding tests. This paper presents the service module expanding tests of which involves of orbit maneuver strategy design and implement results of lunar orbit phasing and lunar long-range rendezvous. The orbit phasing test was carried out in February 6th to 7th 2015. The service module has completed the phasing test through three-impulse orbit maneuver sequence, which simulated the Chang'e-5's orbit module to produce the lunar rendezvous orbit condition during the lander sampling on the moon surface. The long-range rendezvous test was conducted in March 3rd to 8th 2015, comprised of two stages: firstly the service module's orbit was reduced from the circular trajectory of 200km to the ellipse trajectory with the perilune height of 18km and the apolune height of 180km through three-impulse orbit maneuver sequence. Secondly the service module carried out four-impulse orbit maneuver sequence of long-range rendezvous to simulate the Chang'e-5 ascent module flight from 18km high above the lunar surface to arrive at the appropriate rendezvous position of 200km circular orbit. This test's second stage flight imitated the process of the Chang'e-5 ascent module conducting the lunar orbit rendezvous. The trajectory maneuver strategies and the flight data of the lunar phasing test and the lunar rendezvous test will provide a variety of value references for Chang'e-5 mission.*

Keywords: *Chang'e-5 Reentry Flight Experiment, Lunar Orbit Phasing, Lunar Orbit Rendezvous.*

1. Introduction

Chang'e-5 is the first lunar sample return probe of China's Chang-e third stage project sample return mission. After Chang'e-5 probe landing on the moon, it will collect soil samples on the lunar surface and package them into the ascent module of the lander. The ascent module will blast off from lunar surface into lunar orbit and actively rendezvous with the union-module of the orbit module and the return capsule along with delivering the samples to the return capsule. The orbit module will ignition to return the earth carrying with the return capsule and separate out from the return capsule into the space before entering the atmosphere. The return capsule will reentry the atmosphere through the way of leaping and finally land on the earth after being decelerated repeatedly by the atmosphere. There are four main technical difficulties of Chang'e-5 with the lunar orbit rendezvous and docking, the lunar surface sampling, the lunar surface lifting up and the high speed return to the earth.

Chang'e-5 reentry flight experiment (CE-5T1) is a flight test for Chang'e-5 mission. The vehicle was launched in October 24th 2014, consisted of the service module and the return capsule. On November 1st 2014, the return capsule separated from the service module and landed on the earth smoothly, which indicated CE-5T1 mission being successful.

Afterwards, the service module raised up orbit to continue the next expanding test. During the first period of the expanding test, the service module has completed two orbit experiments, one is the large elliptical orbit experiment with the apogee of 540,000km and the perigee of 600km, the other is orbit surrounding of the earth-moon L2 point and returning to the moon experiment.

After that, the service module continued to conduct the lunar orbit rendezvous verification for Chang'e-5 mission. In the expanding test second and third periods, the service module has played two roles of the orbit module and the ascent module for Chang'e-5. During the second period the service module has conducted the lunar phasing orbit maneuver test for being replaced with the Chang'e-5 orbit module and in the third period the service module has completed the lunar orbit rendezvous maneuver test for being replaced with the Chang'e-5 ascent module.

The orbit phasing test was carried out in February 6th to 7th 2015. The service module has completed the phasing test through three-impulse orbit maneuver sequence, which simulated the Chang'e-5's orbit module to produce the lunar rendezvous orbit condition during the lander sampling on the moon surface. The long-range rendezvous test was conducted in March 3rd to 8th 2015, comprised of two stages: firstly the service module's orbit was reduced from the circular trajectory of 200km to the ellipse trajectory with the perilune height of 18km and the apolune height of 180km through three-impulse orbit maneuver sequence. Secondly the service module carried out four-impulse orbit maneuver sequence of long-range rendezvous to simulate the Chang'e-5 ascent module flight from 18km high above the lunar surface to arrive at the appropriate rendezvous position of 200km circular orbit.

Table 1 gives the main task sequences of CE-5T1's service module.

Table 1. Main Task Sequences of CE-5T1's Service Module

Event	Execute Time/BJT	Comment
Injection	2014-10-24	Enter circumlunar free return trajectory
Translunar trajectory and transearth trajectory	From 2014-10-24 to 2014-10-30	Three times of TCM
Return capsule separated from service module	2014-11-01	Return capsule reentry and land on the earth
Avoidance maneuver	2014-11-01	Raise up service module orbit and enter orbit of 16-day period of large elliptical parking orbit
Large eclipse	From 2014-11-01 to 2014-11-21	Four times of orbit maneuver in large Eclipse orbit to enter translunar trajectory
From the moon to LL2	2014-11-23	Orbit maneuver at perilune for flying to and circling LL2
LL2 TCM	2014-11-28	Insertion of LL2's Lissajous trajectory
LL2 orbit maintain	From 2014-12-11 to 2014-12-26	Two times of LL2 orbit maintain maneuver
Escape from LL2	2015-01-04	Return to the moon with perilune height of 200km, lunar inclination of 43.8°
LOI	From 2015-01-11 to 2015-01-13	Three times of LOI to reduce lunar orbit period to 8 hours, 3.5 hours and 127 minutes in proper order
Phasing test	From 2015-02-06	Phasing test with height, eccentricity,

	to 2015-02-10	latitude argument meet for LRR terminal point requirements
Orbit descending stage	From 2015-03-03 to 2015-03-05	Orbit descent with perilune height of 18km and apolune height of 180km to meet LRR initial point requirements
LRR test	From 2015-03-05 to 2015-03-08	LRR test with relative position and velocity to meet LRR terminal point requirements

Note: (1) The time in this paper is based on Beijing time.
(2) LRR is abbreviation of Long-Range Rendezvous.
(3) LOI is abbreviation of Lunar Orbit Insertion.
(4) TCM is abbreviation of Trajectory Correction Maneuver.
(5) LL2 is abbreviation of Lunar-earth Libration point 2.

2. CE-5T1's Phasing Test

2.1. The phasing Test's Orbit Maneuver Objectives and Strategies

(1) The phasing test's orbit maneuver objectives

The purpose of the service module's phasing test is to verify that Change-5's orbit module will carry out several orbit maneuvers for orbit phasing during the assembly of the lander and the riser working on the lunar surface. The orbit module will conduct orbit maneuvers to aim at the orbit objectives of latitude argument, height and eccentricity of LRR terminal point with the orbit module still moving in circular orbit of 200km.

On January 11th 2015, the service module returned to the moon from the earth-moon L2 point and circled the moon after LOI. While the ascending node longitude of lunar orbit was accordance with one of Chang'e-5 after LOI, it launched the phasing test from February 6th to 10th 2015.

The target orbital parameters of the service module's phasing test are set to be in Tab. 2.

Table 2. Target Orbital Parameters of Phasing Test

Circle number	LRR terminal time/BJT	a_{aim} /km	e_{aim}	u_{aim} /°
312	2015-02-10T03:24:38	1937.4	0.0	246.5

Note: (1) The circle number is started from lunar circle orbit formation after LOI.
(2) The orbital elements are defined in J2000 lunar-center inertial coordinate system.
(3) The target orbital parameters consist of a_{aim} as semi-major axis, e_{aim} as eccentricity, u_{aim} as latitude argument at the appointed LRR terminal time.

(2) The phasing test's orbit maneuver strategies

Referring to Chang'e-5 orbit design, the service module plans three-impulse technique in the phasing test. The phasing test goes through four days with three-impulse orbit maneuver sequence in the first two days (corresponding with Chang'e-5 lunar surface operation period) to achieve the objectives of height, eccentricity and latitude argument of LLR terminal point on the fourth day. Before the phasing test, the service module's orbit is nearly circular orbit with height of 200km, and the target orbit of the phasing test is also height of 200km circular orbit. As illustrated in Fig. 1.

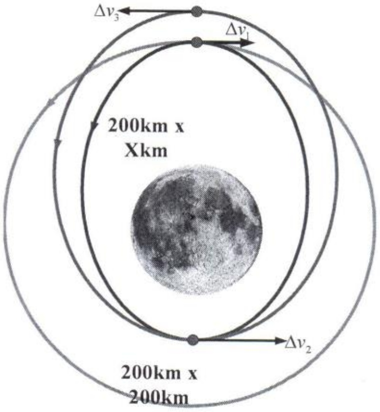

Figure.1 Orbit Maneuver Sketch of Phasing Test

In the Fig.1 the orbit of $200km$ X xkm is phase modulation orbit with Δv_1 as the first impulse by raising orbit height to modulate phase. The second impulses of Δv_2 is used to adjust perilune height and the third impulses of Δv_3 is used to reduce apolune height and make orbit round.

Consideration that there should be adequate time between maneuvers to allow for required tracking and maneuver preparation with the ground support, the circle number and the ignition position of three maneuvers located are determined. As listed in Tab. 3.

Table 3. Orbit Maneuver Strategy of Phasing Test

Serial	Date	Circle number	Ignition position	Impulse	Effect
1	2015-02-06	268	Latitude argument of 60°	Δv_1^t	Raise height to modulate phase
2	2015-02-07	278	Latitude argument of 220°	Δv_2^t	Adjust perilune height
3	2015-02-07	286	u_3 of Perilune nearby	Δv_3^t	Reduce apolune height to round orbit

The phasing test nominal orbital maneuver strategy is that the service module conducts three-impulse sequence with planning variables expressed as $X = \left[\Delta v_1^t, \Delta v_2^t, \Delta v_3^t, u_3\right]$ aiming at four target orbit parameters $Y = \left[a, e_x, e_y, u\right]$ at the appointed LLR terminal point. The first and second ignition positions are predetermined on the basis of ground support and $\Delta v_1^t, \Delta v_2^t, \Delta v_3^t$ are tangential impulses.

According to the nominal orbital maneuver strategy, the increment of Δv_3^t is larger than the one of Δv_2^t, so the third impulse ignition position as u_3 is chosen as planning variable instead of u_2 for stronger adjustment performance.

2.2. The Phasing Test's Orbit Maneuvers Planning

(1) The first planning of phasing test's orbit maneuvers
The phasing test first planning's main task is to determine the size of the first impulse to modulate orbit phase. According to the nominal orbit maneuver strategy, the planning variables $X = \left[\Delta v_1^t, \Delta v_2^t, \Delta v_3^t, u_3\right]$ aim at the target parameters $Y = \left[a, e_x, e_y, u\right]$.
The values of impulse velocity increment and firing time of the normal orbit maneuver sequences are accepted as the initial values of the first orbit maneuver sequence planning. Differential-Correction (DC) algorithm is used to solve the maneuver sequence planning variables iteratively. When there is only one variable of the ignition position or the firing time in the planning variables, DC algorithm usually has good convergence property.

(2) The second planning of phasing test's orbit maneuvers
In the actual flight, due to the influence of various error factors the orbit terminal state always deviates from the target values. After the first orbit maneuver finish, to accurately aim at target orbital parameters, it is needed to add the ignition position of the second orbit maneuver as planning variable.
The phasing test second planning's main task is to determine the size and the firing time of the second impulse to adjust perilune height.
The second planning of orbit maneuver is that the planning variables $X = \left[\Delta v_2^t, u_2, \Delta v_3^t, u_3\right]$ aim at the target parameters $Y = \left[a, e_x, e_y, u\right]$.
The values of impulse velocity increment and firing time of the first orbit planning maneuver sequences are accepted as the initial values, using DC algorithm to solve the maneuver sequence planning variables iteratively.
Because there are two variables of ignition position in the second planning variables, when the actual orbit state deviates a bit much, DC algorithm sometimes is not effective. If DC algorithm is poor convergent, the following constrained optimization algorithm for aiming at partial target parameters can be used.
By using DC algorithm, the partial parameters of the terminal state $Y = \left[a, e_x, e_y\right]$ are solved by the planning variables $X = \left[\Delta v_2^t, \Delta v_3^t, u_3\right]$. Under the inequality constraints of $u_2 - \Delta u_2 \le u_2 \le u_2 + \Delta u_2$, the objective function $J = |u - u_{aim}|$ is to find the optimal value of the objective function as $\min J(u_2)$.

(3) The third planning of phasing test's orbit maneuvers
The phasing test third planning's main task is to determine the size and the firing time of the third impulse to make orbit round. The third planning variables remain as $X = \left[\Delta v_3^t, u_3\right]$.
Because the number of planning variables is less than the number of target parameters, so only partial target parameters can be aimed or optimization algorithm can be used.
The partial target parameters being aimed can be chosen as $Y = [a, e]$ or $Y = [a, u]$.
Alternatively the partial parameters of the terminal state $Y = \left[a\right]$ is solved by the planning variables of $X = \left[\Delta v_3^t\right]$. Under the inequality constraint of $u_3 - \Delta u_3 \le u_3 \le u_3 + \Delta u_3$, the objective

function $J = k_u \frac{|u-u_{aim}|}{1^\circ} + k_e \frac{|e-e_{aim}|}{0.0001}$ is found the optimal value of the objective function of $\min J(u_3)$. The denominators of $1^\circ, 0.0001$ are allowable errors of eccentricity and latitude argument. The weighted coefficients of the objective function can be chosen as $k_u = 1, k_e = 20$.
The orbit maneuver planning strategies in phasing test are summarized in Tab.4.

Table 4. Orbit Maneuver Planning in Phasing Test

Serial	Planning Variables	Target Parameters
1	$X = \left[v_1^t, v_2^t, v_3^t, u_3\right]$	$Y = \left[a, e_x, e_y, u\right]$
2	$X = \left[v_2^t, u_2, v_3^t, u_3\right]$	$Y = \left[a, e_x, e_y, u\right]$
3	$X = \left[v_3^t, u_3\right]$	$Y = \left[a, e\right], Y = \left[a, u\right], Y = \left[a, e, u\right]$

2.3. The Implementation Results of Phasing Test

From February 6th to 10th 2015, the service module carried out the phasing test. With the actual orbit determination and orbit maneuver error situation, the orbital maneuver planning results are listed in the following tables.

Table 5. Orbit Maneuver Planning Results of Phasing Test

Serial	Maneuver 1		Maneuver 2		Maneuver 3	
	Firing Time /BJT	Delta-V /m/s	Firing Time /BJT	Delta-V /m/s	Firing Time /BJT	Delta-V /m/s
1	**15-02-06 03:05:42**	**22.250**	15-02-07 02:13:29	1.892	15-02-07 19:14:09	-23.701
2			**15-02-07 02:22:23**	**1.675**	15:02-07 19:13:30	-23.586
3					**15-02-07 19:13:31**	**-23.615**

Note: The bold data in the table are orbit maneuver parameters for the service module implementing in the phasing test.

Table 6. Achieved LLR Terminal Orbit Parameters of Phasing Test

Parameters	Target orbit status	Actual orbit status	deviations
LLR terminal point time	2015-02-10T03:24:38	2015-02-10T03:24:38	0.0
Semi-major axis/km	1937.4	1937.2	-0.2
eccentricity	0.0	0.0003	0.0003
Argument of latitude /°	246.5	247.8	1.3

3. CE-5T1’s Rendezvous Test’s Orbit Descending Stage

3.1. The Descending Stage’s Orbit Maneuver Objectives and Strategies

1）The descending stage’s orbit maneuver objectives

After the phasing test, the service module stayed in circle orbit of 200km around the moon, waiting for the opportunity of rendezvous test. After about one month, the service module’s orbit was once again content with the constraint conditions of the orbit ascending node longitude being accordance with one of Chang’e-5 after LOI. Within 2 days, the service module conducted several orbit maneuvers to attain LLR initial orbit conditions.

The LLR initial orbit conditions are referred to that the service module arrives at perilune point at the appointed time with the local orbital altitude of 18km and else the latitude argument of 107° and the apolune height of 180km. The LLR initial orbit is simulation of the injection orbit of Chang’e-5’s ascent module.

From March 3rd to 5th 2015, the service module executed descending orbit maneuvers. The target orbital parameters of the service module’s descending stage are set to be in Tab.7. The target orbital parameters consist of perilune height as h_{paim}, apolune height as h_{aaim}, perilune argument as ω_{aim} and true anomaly as f_{aim} at the appointed LRR initial time.

Table 7. Target Orbital Parameters of Descending Stage

Circle number	LLR initial time/BJT	h_{paim}/km	h_{aaim}/km	ω_{aim}/°	f_{aim}/°
582	2015-03-05T21:45:00	18.0	180.0	108.0	0.0

2）The descending stage’s orbit maneuver strategies

Within 2 days the service module conducted three orbit maneuvers to get to the perilune point at the appointed time with the perilune height, the apolune height and the latitude argument being content with target values. As illustrated in Fig. 2.

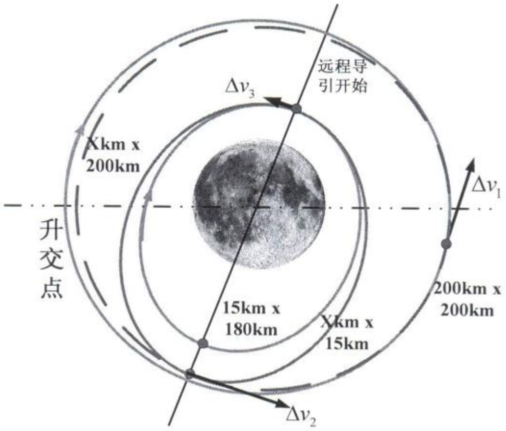

Figure.2 Orbit Maneuver Sketch of Descending Stage

In the Fig.2, the first impulse of Δv_1 reduces orbit height to adjust orbit period for the service module to get to the perilune point at the appointed time in about 2 days. The size and the firing time of the second impulse of Δv_2 are used to aim at the perilune height and the perilune argument of LRR initial orbit. The third impulse of Δv_3 is used to modulate apolune height at the perilune point.

Consideration with the ground support, three orbit maneuvers' circle numbers and ignition positions of the descending stage are determined. As listed in the follow table.

Table 8. Orbit Maneuver Strategy of Descending Stage

Serial	Date	Circle number	Ignition position	Impulse	Effect
1	2015-03-03	558	Latitude argument of 255°	Δv_1^t	Reduce orbit to modulate period
2	2015-03-04	569	u_2 of Apolune point nearby	Δv_2^t	Adjust perilune height and perilune argument
3	2015-03-05	573	Perilune point	Δv_3^t	Correct apolune height

The descending stage nominal orbital maneuver strategy is that the service module conducts three-impulse sequence with planning variables expressed as $X = \left[v_1^t, v_2^t, u_2, v_3^t\right]$ aiming at four target orbit parameters of $Y = \left[h_p, h_a, \omega, f\right]$ at the appointed LLR initial point. The first ignition position is predetermined on the basis of ground support and $\Delta v_1^t, \Delta v_2^t, \Delta v_3^t$ are tangential impulses. According to the nominal orbital maneuver strategy, the increment of Δv_2^t is large than the one of Δv_3^t, so the second impulse ignition position as u_2 is chosen as planning variable instead of u_3 for stronger adjustment performance .

3.2. The Descending Stage's Orbit Maneuvers Planning

(1) The first planning of descending stage's orbit maneuvers

The descending stage first planning's main task is to determine the size of the first impulse to adjust orbit period. According to the nominal orbit maneuver strategy, the planning variables $X = \left[v_1^t, v_2^t, u_2, v_3^t\right]$ aim at the target parameters $Y = \left[h_p, h_a, \omega, f\right]$. The values of impulse velocity increment and firing time of the normal orbit maneuver sequences are accepted as the initial values of the first orbit maneuver sequence planning. DC algorithm is used to solve the maneuver sequence planning variables iteratively.

(2) The second planning of descending stage's orbit maneuvers

To accurately aim at target orbital parameters, after the first orbit maneuver finish, the ignition position of the third orbit maneuver is added as design variable.

The descending stage second planning's main task is to determine the size and the firing time of the second impulse to adjust the perilune height and the perilune argument. The second planning of orbit maneuver is that the planning variables expressed as $X = \left[\Delta v_2^t, u_2, \Delta v_3^t, u_3\right]$ aim at the target parameters as $Y = \left[h_p, h_a, \omega, f\right]$. DC algorithm is used solve the maneuver sequence planning variables iteratively.

Since the purpose of descending stage is to prepare the initial orbit for LLR test, no precise orbit accuracy is needed. Therefore, if DC algorithm is false, only partial target parameters can be aimed at. For example, the partial parameters of $Y=\left[h_p,\omega,f\right]$ are solved by the planning variables of $X=\left[\Delta v_2^t,u_2,\Delta v_3^t\right]$ by DC algorithm.

(3) The third planning of descending stage's orbit maneuvers

The descending stage third planning's main task is to determine the size and the firing time of the third impulse to adjust the apolune height. The planning variables are expressed as $X=\left[\Delta v_3^t,u_3\right]$. Since the orbit requirement of LLR initial point is not strict, the reduction of the target parameters is accepted. There are several options of the target parameters such as $Y=\left[h_p,\omega\right]$, $Y=\left[h_p,f\right]$, $Y=\left[h_p,h_a\right]$ to choose.

The orbit maneuver planning strategies in descending stage are summarized in Tab.9.

Table 9. Orbit Maneuver Planning in Descending Stage

Planning	Planning Variables	Target Parameters
1	$X=\left[v_1^t,v_2^t,u_{2,}v_3^t\right]$	$Y=\left[h_p,h_a,\omega,f\right]$
2	$X=\left[v_2^t,u_2,v_3^t,u_3\right]/X=\left[v_2^t,u_2,v_3^t\right]$	$Y=\left[h_p,h_a,\omega,f\right]/Y=\left[h_p,\omega,f\right]$
3	$X=\left[v_3^t,u_3\right]$	$Y=\left[h_p,f\right],Y=\left[h_p,f\right],Y=\left[h_p,f\right]$

3.3. The Implementation Results of Descending Stage

From March 6th to 5th 2015, the service module carried out orbit descending. With the actual orbit determination and orbit maneuver error situation, the orbital maneuver planning results are listed in the following table.

Table 10. Orbit Maneuver Planning Results of Descending Stage

Serial	Maneuver 1		Maneuver 2		Maneuver 3	
	Firing Time /BJT	Delta-V /m/s	Firing Time /BJT	Delta-V /m/s	Firing Time /BJT	Delta-V /m/s
1	**15-03-03 22:13:43**	**-14.076**	15-03-04 21:04:37	-26.600	15-03-05 04:05:22	-3.118
2			**15-03-04 21:05:17**	**-25.854**	15-03-05 04:13:43	-3.648
3					**15-03-05 04:11:12**	**-3.564**

Table 11. Achieved LLR Initial Orbit Parameters of Descending Stage

Parameters	Target orbit status	Actual orbit status	deviations
LRR initial point time	2015-03-05T21:45:00	2015-03-05T21:45:00	0.0
Perilune height/km	18.0	17.935	-0.065
Apolune height/km	180.0	180.186	0.186
Perilune argument/°	108.8	108.368	0.368
True anomaly/°	0.0	359.656	-0.344

4. CE-5T1's Rendezvous Test's Long-Range Rendezvous Test

4.1. The LLR Test's Orbit Maneuver Objectives and Strategies

(1) The LLR stage's orbit maneuver objectives

At the LLR stage, with the support of the ground control center, the service module conducts four-impulse orbit maneuver sequence to correct the orbit differences of the service relative to the virtual target vehicle and finally reaches the LLR terminal point of about 50km away from the virtual target, where the virtual target's orbit parameters are predetermined at the appointed LLR terminal time.

The virtual target vehicle is defined in the round orbit with height of 200km and latitude argument of 280°at the LLR terminal point. The service module enters round orbit with height of 210km being coplanar with the virtual target orbit. At the LLR terminal point, the service module will be located at 10km upper and 50km forward of the virtual target vehicle.

The target orbital parameters of the service module's LLR test are set to be in the Tab.12. At the appointed LLR terminal point, the relative position and velocity components of the service module relative to the virtual target vehicle in the virtual target's LVLH coordinate system.

Table 12. Target Orbital Parameters of LLR Test

Circle number	LLR terminal time/BJT	x_{aim} /km	y_{aim} /km	z_{aim} /km	$\dot{x}_{aim}$ /m/s	$\dot{y}_{aim}$ /m/s	$\dot{z}_{aim}$ /m/s
25	2015-03-08T00:42:00	50.0	0.0	-9.4	-12.3	0.0	-0.3

(2) The LLR's orbit maneuver strategies

According to Chang'e-5's orbit design, the service module plans four-impulse technique in the LLR test. As illustrated in Fig. 3. The service orbit executes four orbit maneuvers within 2 days to reach the position of about 50km forward of the virtual target vehicle at the appointed LLR terminal time.

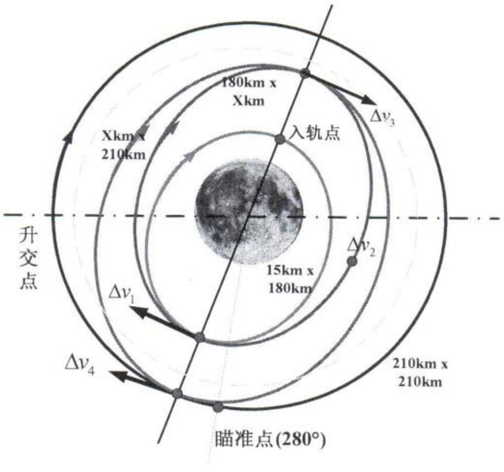

Figure.3 Orbit Maneuver Sketch of LLR Test

In the Fig.3, Δv_1 is the first impulse to adjust orbit phase; Δv_2 is the second impulse to correct orbit plane; and the third and the fourth impulses of Δv_3 and Δv_4 are used to modulate perilune height and apolune height in the orbital plane.

The circle number and the ignition position of the impulses except for the second impulse are determined on the basis of the ground support. As listed in Tab. 13.

Table 13. Orbit Maneuver Strategy of LLR Test

Serial	Date	Circle	Ignition position	Impulse	Effect
1	2015-03-06	3	latitude argument of 283°	Δv_1^t	Raise perilune height
2	2015-03-06	9	u_2 of orbit planes cross point	Δv_2^n	Correct orbit plane
3	2015-03-07	15	u_3 of perilune nearby	Δv_3^t	Correct apolune height
4	2015-03-07	22	u_4 of apolune nearby	Δv_4^t	Round orbit

The LLR test nominal orbital maneuver strategy is that the service module conducts four-impulse sequence with planning variables expressed as $X = \left[\Delta v_1^t, \Delta v_2^n, u_2, \Delta v_3^t, \Delta v_t^t, u_4\right]$ aiming at six target state parameters as $Y = \left[x, y, z, \dot{x}, \dot{y}, \dot{z}\right]$ of the LLR terminal point. The first ignition position is predetermined on the basis of ground support and $\Delta v_1^t, \Delta v_3^t, \Delta v_4^t$ is tangential impulse and Δv_2^n is normal impulse.

4.2. The LLR Test's Orbit Maneuvers Planning

(1) The first planning of LLR test's orbit maneuvers

The LLR test first planning's main task is to determine the size of impulse to adjust orbit phase.

According to the nominal orbit maneuver strategy, the planning variables of $X = \left[\Delta v_1^t, \Delta v_2^n, u_2, \Delta v_3^t, \Delta v_t^t, u_4\right]$ aim at the target parameters of $Y = \left[x, y, z, \dot{x}, \dot{y}, \dot{z}\right]$.

The values of impulse velocity increment and firing time of the normal planning orbit maneuver sequences are accepted as the initial values of the first maneuver sequence planning by Using DC algorithm to solve the maneuver sequences' planning variables iteratively.

(2) The second planning of LLR test's orbit maneuvers

To accurately aim at target orbital parameters, after the first orbit maneuver, the ignition position of the third orbit maneuver is added as design variable.

The LLR test second planning's main task is to determine the size and firing time of the orbit plane correction impulse.

The planning variables expressed as $X = \left[\Delta v_2^n, u_2, \Delta v_3^t, u_3, \Delta v_t^t, u_4\right]$ are aiming at the target states as $Y = \left[x, y, z, \dot{x}, \dot{y}, \dot{z}\right]$ of the relative position and velocity of LLR terminal point and DC algorithm is used to solve the maneuver sequences' planning variables iteratively.

If DC algorithm is poor convergent, the following constrained optimization algorithm for aiming at partial target parameters can be used.

By using DC algorithm, the partial parameters of the terminal state of $Y = \left[x, y, z, \dot{y}, \dot{z}\right]$ are solved by the planning variables of $X = \left[\Delta v_2^n, \Delta u_2, \Delta v_3^t, \Delta v_4^t, u_4\right]$. Under the inequality constraints of $u_3 - \Delta u_3 \le u_3 \le u_3 + \Delta u_3$, the objective function $J = \left|\dot{x} - \dot{x}_{aim}\right|$ is to find the optimal value of the objective function of $\min J(u_3)$.

(3) The third planning of LLR's test orbit maneuvers

The main task of the third planning is to determine the size and firing time of the apolune height correction impulse. The planning variables of the third maneuver plan expressed as $X = \left[\Delta v_3^t, u_3, \Delta v_t^t, u_4\right]$ are aiming at the target states $Y = \left[x, z, \dot{x}, \dot{z}\right]$ of the relative position and velocity of LLR terminal point. And later no more of the orbit plane correction. The third planning is almost same as the second planning.

The fourth planning of LLR test's orbit maneuvers

The main task of the fourth planning is to determine the size and firing time of the circling orbit. The planning variables of the fourth maneuver plan expressed as $X = \left[\Delta v_4^t, u_4\right]$ are aiming at the target states $Y = \left[x, z, \dot{x}, \dot{z}\right]$ of the relative position and velocity of the long-range rendezvous terminal point.

Because the number of the planning variables is less than the number of the target state parameters, the following constrained optimization algorithm for aiming at partial target parameters can be used.

By using the DC algorithm, the partial parameters of the terminal state of $Y = \left[x\right]$ are solved by the planning variables of $X = \left[\Delta v_4^t\right]$. Under the inequality constraints of $u_4 - \Delta u_4 \le u_4 \le u_4 + \Delta u_4$, the objective function $J = \sqrt{k_z \left| z - z_{aim} \right| + k_{\dot{x}} \left| \dot{x} - \dot{x}_{aim} \right| + k_{\dot{z}} \left| \dot{z} - \dot{z}_{aim} \right|}$ is to find the optimal value of the objective function as $\min J(u_4)$ with $k_z = 1, k_{\dot{x}} = 1000, k_{\dot{z}} = 1000$.

The orbit maneuver planning strategies in LLR test are summarized in Tab.14.

Table 14. Orbit Maneuver Planning in LLR test

Serial	Planning variables	Target parameters
1	$X = \left[\Delta v_1^t, \Delta v_2^n, u_2, \Delta v_3^t, \Delta v_t^t, u_4\right]$	$Y = \left[x, y, z, \dot{x}, \dot{y}, \dot{z}\right]$
2	$X = \left[\Delta v_2^n, u_2, \Delta v_3^t, u_3, \Delta v_t^t, u_4\right]$	$Y = \left[x, y, z, \dot{x}, \dot{y}, \dot{z}\right]$
3	$X = \left[\Delta v_3^t, u_3, \Delta v_t^t, u_4\right]$	$Y = \left[x, z, \dot{x}, \dot{z}\right]$
4	$X = \left[\Delta v_t^t, u_4\right]$	$Y = \left[x, z, \dot{x}, \dot{z}\right]$

4.3. The Implementation Results of LLR Test

From March 6th to 8th 2015 the service module carried out the LLR test. With the actual orbit determination and orbit maneuver error situation, the orbital maneuver planning results of LLR are listed in the following table.

Table 15. Orbit Maneuver Planning Results of LLR Test

Serial	Maneuver 1		Maneuver 2		Maneuver 3		Maneuver 4	
	Firing time /BJT	Delta-V /m/s	Firing time /BJT	Delta-V /m/s	Firing time /BJT	Delta-V /m/s	Firing time /BJT	Delta-V /m/s
1	**15-03-06 02:37:03**	**32.64**	15-03-06 14:15:24	1.64	15-03-07 02:26:33	5.95	15-03-07 18:19:17	9.48
2			**15-03-06 14:16:13**	**1.49**	15-03-07 02:29:29	5.75	15-03-07 18:20:00	9.53
3					**15-03-07 02:30:09**	**5.73**	15-03-07 18:20:	9.53
3							**15-03-07 18:20:14**	**9.48**

Table 16. Achieved Terminal State Parameters of LLR Test

Parameter	Target orbit status	Actual orbit status	deviation
LRR terminal time	2015-03-08T00:42:00	2015-03-08T00:42:00	0.0
x /km	50.0	48.0	2.0
y /km	0.0	-0.2	-0.2
z /km	-9.4	-9.7	-0.3
$\dot{x}$ /m/s	-12.3	-12.8	-0.5
$\dot{y}$ /m/s	0.0	0.1	0.1
$\dot{z}$ /m/s	-0.3	-0.7	-0.4

5. Conclusions

In the CE-5T1's lunar rendezvous expanding test, the service module has completed the orbit phasing test and the long-range rendezvous test along with the orbit descending stage. The three-impulse sequence technique of orbit phasing strategy and the four-impulse sequence technique of long-range rendezvous strategy were verified and very good orbit maneuver results were achieved.

The service module's flight has also verified the related technologies for Chang'e-5 mission, including the trajectory maneuver strategies of the lunar orbit phasing and the lunar long-range rendezvous, the ground and onboard cooperative regulate sequences, trajectory measurement and flight control precision, especially the lunar orbit rendezvous nominal trajectory design and scheme being assessed. The test data and experiences will provide a variety of value references for Chang'e-5 mission.