Orbital Support for China's Chang'E-2 Lunar Exploration Satellite

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The Chang'E-2 satellite, launched in 2010, is the leading satellite of the second phase of China's lunar exploration program. Compared with the Chang'E-1 satellite launched in 2007, the orbit requirements of Chang'E-2, such as the complex orbit maneuver technology, high-precision X-band measurement technology experiment etc, are much higher. For the ground TT&C system, the accurate estimation of the orbit determination and prediction about the orbit control is one key technology. Accurate estimation of the experimental data in X-band is another key technology. In this paper a comprehensive analysis of the ground TT&C system's orbital support for Chang'E-2 is discussed, focusing on the orbit determination strategy and accurate assessment methods of various flight phases. Calculated by the ground TT&C system, the results showed that: by using Unified S-Band (USB) and Very Long Baseline Interferometry (VLBI), the orbit prediction accuracy of the midcourse trajectory correction is about 270m, 0.15m/s in 3h advance; the orbit prediction accuracy of the lunar orbit insertion is about 320m, 0.07m/s in 3h advance; the orbit determination accuracy of the lunar mission orbit is tens of meters; the RMS of O-C residuals of the range, range rate, ΔDOR's delay and delay rate of the X-band, are about 1m, 1mm/s, 1ns, 1ps/s respectively and corresponds to about 5 to 10 times better than that of the S-band.

I. Introduction

Chang'E-2 (CE-2) satellite, launched in 2010, is the leading satellite of the second phase of Chinese lunar exploration program, it works on the main task of testing some of the key technologies and new equipments, verifying the new direct earth-moon transfer orbit, reducing the lunar exploration program technology risk; the primary task of science is the detailed investigation of the nominal lunar surface landing area, fine topography surveying and mapping alternative landing areas. CE-2 aims to achieve six major technological breakthrough (Ref. 1)

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for China, of which four are related to launch and TT&C technology. They include: the launch technology of direct earth-moon transfer orbit; the first experimental X-band deep-space TT&C technology; verification of Lunar Orbit Insertion (LOI) at the altitude of 100 km; verification of the orbital maneuver and orbit tracking and determination technology. Implementation and evaluation of these key technologies rely heavily on the support of the ground TT&C system network, especially the achievement of high-precision satellite orbit data.

At the beginning of the lunar exploration program, the ground TT&C system network through demonstration and simulation calculation (Ref. 2-3), adopted the Unified S-band system (USB) and Very Long Baseline Interferometry (VLBI) for the joint orbit tracking and determination, and in 2005 and 2006, the USB and VLBI joint orbit determination experiments were carried out with TC-1 satellite and the European Space Agency (ESA) lunar spacecraft SMART-1 (Ref. 4-5), during which the measurement mode, the orbit determination software was validated. Chang’E-1 (CE-1) , launched in 2007, using USB and VLBI for the orbit determination, achieved orbit prediction accuracy to be on the order of one hundred meters in position and 10cm/s in velocity for midcourse correction maneuver and LOI, and the orbit determination accuracy to be about a few ten meters for the lunar mission orbit (Ref. 6). Compared with the CE-1 satellite, the CE-2 satellite orbit, including the direct earth-moon transfer phase, LOI at the altitude of 100km, 100km×100km and 100km×15km lunar mission orbit, calls for higher orbit determination and prediction accuracy. In addition, CE-2 satellite also carried out X-band tracking measurement experiment at he earth-moon phase and the lunar mission orbit, the purpose of which is to provide high-precision orbit data support to prepare for future lunar and deep space exploration activities.

The analysis of the orbit determination and prediction accuracy of key orbit control maneuver and assessment of the X-band measurement data quality is an urgent problem for the reference of the ground TT&C system to design follow-up exploration activities. In this paper a comprehensive analysis of orbital support for the CE-2 satellite by the ground TT&C system is provided, and the orbit determination strategies in all phases of flight and methods of accuracy assessment are discussed. Calculated by the ground TT&C system, orbit prediction accuracy of the midcourse correction maneuver and LOI, orbit determination accuracy of the lunar mission orbit which is closely related to the science mission, the RMS of the O-C residuals of X-band measurement data are all given.

II. CE-2 Major Flight Phases and System of Orbit Measurement

Compared with the CE-1 satellite, the CE-2 satellite was launched directly into the earth-moon transfer orbit, orbiting the Moon at the altitude of 100km instead of 200km during lunar mission orbit and carried out X-band tracking technology and measurement experiments. With CE-1 satellite experience, the ground TT&C system continues to jointly use the USB and VLBI with international network to acquire measurement data for orbit determination.

A. Major Flight Phases

CE-2 satellite orbit design inherits the theory and methods (Ref. 7) of those of CE-1 satellite and some adaptive improvements are implemented. Compared with the CE-1 satellite, the course of CE-2 satellite flight does not include the earth phasing stage. Instead, it flies directly into the earth-moon transfer orbit, with subsequent phases of LOI at the altitude of 100km, 100km × 100km and 100km × 15km lunar mission orbit.

CE-2 satellite was launched at 18:59, October 1, 2010 (Beijing time, the same below) and after earth-moon phase (a midcourse correction, at 12:25 pm on October 2) and three LOI maneuvers, successfully entered the 100km circular polar science mission orbit at 11:32 on October 9. After a series of in-orbit testing, the satellite finally set into the lunar exploration stage. At 21:45 on October 26, CE-2 satellite executed maneuver to descend into 100km × 15km orbit so as to map the nominal landing area Sinus Iridum. Then at 10:36 on October 29, CE-2 satellite ascent back to the 100km circular orbit, starting the long-term management phase for subsequent scientific exploration activities.

B. Orbit Measurement System

CE-2 satellite orbit measurement system adopts the same design as that of CE-1 satellite (Ref. 8), namely joint measurement of USB and VLBI together with international network of ESA and processing of all the measurement data for orbit determination by ground control center. USB measurement system consists of stations both domestic and overseas. Domestic stations are Qingdao and Kashi for the orbit measurement; overseas station is Kourou of ESA with the primary function of the TT&C support for the first perilune braking. VLBI measurement system is mainly composed of four VLBI stations, including Shanghai station, Beijing Station, Kunming Station and Urumqi station. USB measurement system provides range and range rate. VLBI measurement system provides delay and delay rate data.

According to the plan, the CE-2 satellite carried out X-band tracking technology and measurement experiments in the earth-moon phase and 100km × 100km, 100km × 15km lunar orbit phase. The detailed design is described in Ref. 9. These experiments also add range, range rate, ΔDOR delay and delay rate data in X-band to the overall data for orbit determination. The arc and stations of the experiments are shown in Table. 1.

Table 1. the arc of the X-band tracking technology and measurement experiments.

orbit	time	station	arc
Transfer phase	2010-10-3	Kashi	two arcs
	2010-10-4	Qingdao	
100km × 100km lunar mission orbit	2010-10-13	Kashi	three arcs
	2010-10-14	Kashi, Qingdao	
	2010-4-2~4-21	Kashi, Qingdao	four arcs for each of 4 days
100km × 15km lunar mission orbit	2010-10-29	Kashi, Qingdao	two arcs

III. Strategy of the Orbit Determination and Prediction of and Accuracy Analysis of the CE-2

Satellite orbit determination techniques include the part of the valuation methods, the integration technique, the parameters for solving the dynamic model and observation model, the theory is relatively mature, specific seeing Ref. 10. The accuracy analysis of CE-2 satellite orbit determination and prediction needs to consider the orbital characteristics, the geometry of the station, the satellite attitude control and other factors. For the transfer orbit and lunar insertion orbit, the prediction accuracy of the orbit control is concerned by the ground TT&C system. For the mission orbit is mainly concerned about the achievement of science missions, so is closely related to the orbit determination accuracy. The strategy of the orbit determination and prediction and accuracy of analysis results from the ground TT&C system is given.

A. Midcourse Correction Maneuver Orbit Determination and Prediction Strategy and Accuracy of Analysis

After entering the transfer orbit about 17h, the ground TT&C system generally provides the location and speed of the midcourse correction maneuver in advance 3h~6h, so as to calculate the ΔV. The precision of the ΔV, in addition to considering the orbit control engine accuracy, but also need to consider the accuracy of orbit prediction, which is the key technical indicator that the ground TT&C system needs to provide.

The transfer orbit of CE-2 is around the Earth's elliptical orbit. The orbital period is long and more flight satellite jet, attitude adjustment action. If using the whole arc for the orbit determination, the result is poor, from the residuals of O-C and the outcome of solving for the non-gravitational acceleration terms are present abnormalities. In order to solve the above problem and give the reasonable prediction accuracy, refering to the orbit determination experience of CE-1 and SMART-1(Ref. 6, 11), this paper proposes the following method:

1) Spliting the observational data for several segments for determining the orbit. The VLBI measurement system participates in tracking after CE-2 entering the transfer orbit about 10h. So the ground TT&C system uses the arc about 7h from the beginning of VLBI tracking to the midcourse correction maneuver to determine the precise orbit. The real-time orbit determination uses the arc before the beginning of the midcourse correction maneuver about 3h, 6h respectively, and predicting to the midcourse correction maneuver start time. Comparing the two ephemerises and giving the maximum value as the forecast accuracy.
2) By solving for the non-gravitational acceleration terms in the orbit determination process, satellite activity effect on the orbit determination is mitigated. For the orbit prediction, we do not solve the non-gravitational acceleration terms.
3) The other orbit determination and prediction strategy as shown in Table. 2.

Calculated in accordance with the above method, prediction accuracy of the midcourse correction maneuver is 270m in position and 0.15m/s in velocity in 3h advance, and 850m in position and 0.54m/s in velocity in 6h advance.

Table 2. midcourse correction maneuver orbit determination and prediction strategy.

content	strategy
the earth's gravitational field	JGM-3
solar radiation pressure	Cr = 1.4
the third body perturbation	JPL DE403/LE403
the non-gravitational acceleration	solving
measurement data	the range and range rate of USB and the delay and delay rate of VLBI
solution Parameter	Orbital elements, Cr, bias of range, the non-gravitational acceleration terms

B. Strategy and Accuracy Analysis of Orbit Determination and Prediction at LOI

LOI at the altitude of 100km is a major technological breakthrough for CE-2 satellite. Compared with CE-1 satellite, perturbation forces, in particular the lunar non-spherical gravitation, have changed greatly because of the altitude changes (Ref. 12-13). It may lead to failure of lunar capture if the orbit prediction and the resulting calculated magnitude of correction is not accurate. Therefore, it is the responsibility of the ground TT&C system to provide accurate orbit prediction results at LOI.

Several satellite events such as attitude adjustment and jetting take place between midcourse trajectory correction and LOI, thus making it difficult to use the whole arc data for post precision orbit determination. Therefore, in order to achieve reasonable LOI orbit prediction accuracy, we propose a method of using the data acquired between LOI and LOI-24h for orbit determination and prediction, taking into account such factors as the characteristics of CE-2 orbit, geometry of ground stations and data processing experiences in CE-1 mission. The method is described as follows:

1) Use the USB and VLBI measurement data between LOI and LOI-24h for post precision orbit determination; Use USB and VLBI measurement data 3h before LOI, 6h before LOI respectively for real-time orbit determination and predict to LOI start time. The maximum difference between the two calculated ephemeris is considered as the prediction accuracy.
2) By solving for the non-gravitational acceleration terms in the orbit determination process, satellite activity effect on the orbit determination is mitigated.
3) Orbit determination strategy is similar to that listed in Table. 2, except for the consideration of lunar non-spherical effect, where the JGL165p1 gravity model is used.

Calculated in accordance with the above method, the accuracy of the orbit prediction to LOI is 320m in position and 0.07m/s in velocity in 3h advance, and 860m in position and 0.33m/s in velocity in 6h advance.

C. Orbit Determination Strategy and Accuracy Analysis of Lunar Mission Orbit

The lunar mission orbit of CE-2 satellite is 100km x 100km circular orbit and 100km × 15km ecliptic orbit with period of about 2h. Compared with CE-1 satellite, perturbation forces, in particular the lunar non-spherical gravitation, have changed greatly because of the altitude change. We therefore use JGL165p1 model to take into consideration of more orders and degrees of lunar gravity field.

Since the tracking arcs of the lunar mission orbit is rather long and considering the effect of satellite activity, we propose a method of dividing the overall arcs into multiple short arcs with USB and VLBI measurement data and using the orbit difference of overlapping arc for the assessment of the orbit determination accuracy. The method is described in detail as follows:

1) For the 100km × 100km lunar mission orbit, the tracking arc between October 23, 2010 and October 26,2010 is divided into five arcs (about 14h of each arc), with overlapping arc of 2h.
2) For the 100km × 15km lunar phase, the tracking arc between October 26, 2010 and October 29,2010 is divided into six arcs (about 12h of each arc, the fifth of which lack VLBI data), with overlapping arc of 2h.
3) By solving the non-gravitational acceleration terms in the orbit determination process, satellite activity effect on the orbit determination is mitigated.
4) The other orbit determination strategy is similar to that listed in Table. 3.

Detailed results of the orbit determination are shown in Table. 4. From that, the orbit determination accuracy of the overlapping arc of the 100km × 100km lunar phase is 26m~63m in position and 0.02m/s ~0.06m/s in velocity;

the orbit determination accuracy of the first to fourth overlapping arc of the 100km × 15km lunar phase is 49m~82m in position and 0.04m/s~0.07m/s in velocity; and the accuracy including the fifth overlapping arc is 5~10 times worse than the other arcs because of the lacking of VLBI data, indicating the importance of the VLBI on orbit determination.

Table 3. lunar mission orbit determination strategy.

content	strategy
The moon's gravitational field	JGL165p1
Solar radiation pressure	Cr = 1.4
the third body perturbation	JPL DE403/LE403
the non-gravitational acceleration	solving
measurement data	the range and range rate of USB and the delay and delay rate of VLBI
Solution Parameter	Orbital elements, Cr, bias of range, the non-gravitational acceleration terms

Table 4. accuracy of the overlapping arc of lunar mission orbit.

arc	100km × 100km		100km × 15km	
	Position(m)	Velocity(m/s)	Position(m)	Velocity(m/s)
arc 1~ arc 2	63	0.06	49	0.04
arc 2~ arc 3	26	0.02	82	0.07
arc 3~ arc 4	39	0.03	55	0.04
arc 4~ arc 5	30	0.02	341	0.32
arc 5~ arc 6	—	—	411	0.36

IV. The Analysis of the X-band Measurement Data Quality

With China's lunar and deep space exploration activities carried out in-depth, the requirements of satellite orbit determination accuracy are getting higher, and an effective way to increase satellite orbit determination accuracy is to improve the measurement accuracy. As is known, the higher the radio frequency, the shorter the wavelength and in turn the higher the measurement accuracy. Foreign deep space network equipment generally uses the X/Ka-band. For X-band, the measurement accuracy of range and range rate data are 5m and 0.5mm/s respectively (Ref. 14). In order to test and enhance high-precision orbit tracking technology, the ground TT&C systems use CE-2 satellite to carry out the X-band tracking technology and measurement experiments. Taking into account the other experiment arrangements, the tracking arc allocated for X-band experiments is relatively short. Therefore, it tends out to be a key challenge for us to address how to assess the measurement data quality. In this paper, we propose a method to use the post precision orbit ephemeris of each flight phase, which is determined jointly by USB, VLBI and X-band measurement data, to evaluate the corresponding data quality. The procedures are as follows:

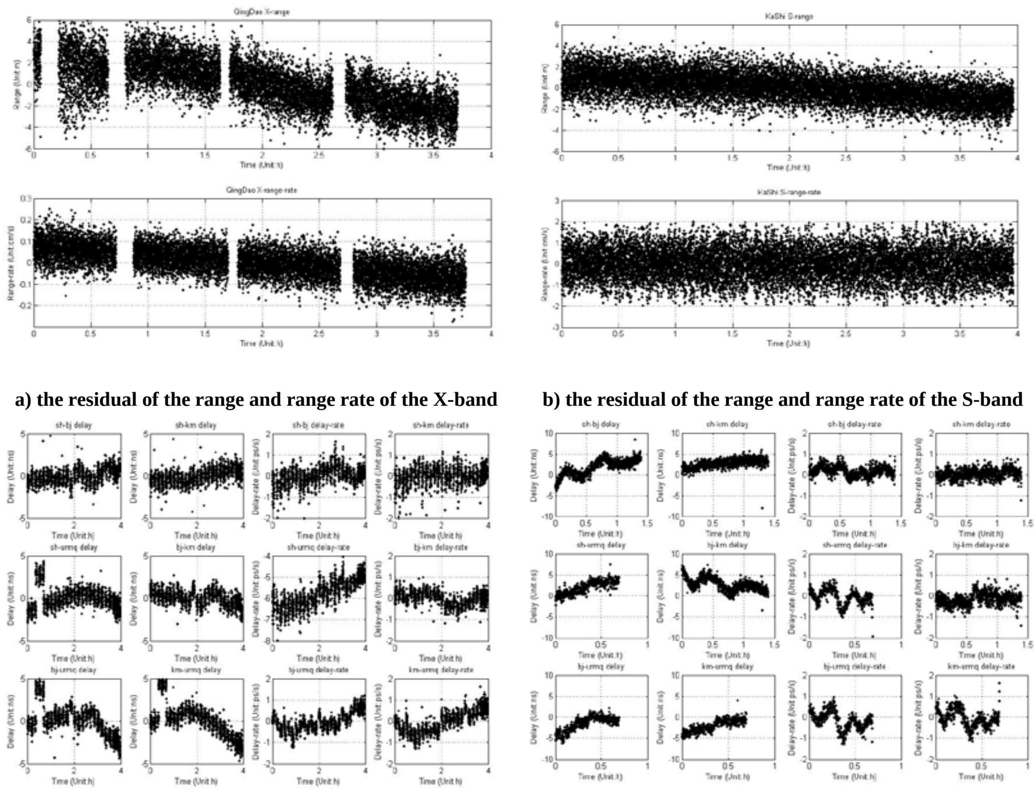
1) For the transfor phase, the USB range and range rate data and VLBI delay and delay rate data (about 24h) as well as the range and range rate data of the 2h X-band experiment acquired from each station on October 3 and October 4 are used to carry out the orbit determination, the strategy of which is similar to 3.1;
2) For 100km × 100km and 100km × 15km lunar mission orbit, the USB range and range rate data and VLBI delay and delay rate data (about 10h) as well as the range, range rate, ΔDOR delay and delay rate data of the 2h X-band experiment acquired from each station are used to carry out the orbit determination, the strategy of which is similar to 3.2.

According to the X-band measurement data residuals resulting from the analysis of precision orbit determination, the results can be summarized as follows:

1) The RMS of O-C residuals of the range of the X-band is 5 times less than that of the S-band range data, which is about 1m and 5m respectively;
2) The RMS of O-C residuals of the range rate of the X-band is at least an order of magnitude better than that of the S-band, which is about 1mm/s and 1cm/s~3cm/s respectively;
3) The RMS of O-C residuals of the X-band ΔDOR delay data is 5 times less than that of the VLBI delay data, which is about 1ns~2ns and 5ns respectively;

4) The RMS of O-C residuals of the X-band ΔDOR delay rate data is comparable with that of the VLBI delay rate data, which is 0.3ps/s~1ps/s.

It is shown in Fig. 1 that the residuals of the measurement data acquired from part of the X-band experiment tracking arc on October 4, 2010.



a) the residual of the range and range rate of the X-band

b) the residual of the range and range rate of the S-band

c) the residual of the delay and delay rate of the X-band

d) the residual of the delay and delay rate of the S-band

Figure 1. the residuals of the measurement data acquired from part of the X-band experiment tracking arc on October 4, 2010.

V. Conclusion and Discussion

This paper analyzes the accuracy of orbit determination and prediction from the viewpoint of mission requirements. Efforts can be made to increase the accuracy by taking advantage of better tracking arcs and estimating non-gravitational acceleration terms in the orbit determination process. The strategy of orbit determination can also be optimized to make in-depth analysis of more data.

Thanks to precise navigation and control by the ground TT&C systems, CE-2 satellite has fulfilled its objectives and continued on extended missions. Through the analysis of the orbit determination and prediction accuracy of CE-2 satellite and X-band measurement data quality, the feasibility and reliability of the calculation software and strategy of orbit determination is verified and a valuable reference is provided for the future design of the ground TT&C system.

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