Orbit Determination for CE5T Based upon GPS Data

Cao Jianfeng(1)**, Tang Geshi**(2)**, Hu Songjie**(3)**, ZhangYu**(4)**, and Liu Lei**(5)

(1)*Beijing Aerospace Control Center, 26 Beiqing Road, Haidian Disrtrict, Beijing, +86 013811206835, jfcao@foxmail.com*

(2)*Beijing Aerospace Control Center, 26 Beiqing Road, Haidian Disrtrict, Beijing,+86 013521927896, tanggeshi@bacc.org.cn*

(3)*Beijing Aerospace Control Center, 26 Beiqing Road, Haidian Disrtrict, Beijing,+86 013581833957, husongjie@aliyun.com*

(4)*Beijing Aerospace Control Center, 26 Beiqing Road, Haidian Disrtrict, Beijing,+86 01340164578, zackyzy@163.com*

(5)*Beijing Aerospace Control Center, 26 Beiqing Road, Haidian Disrtrict, Beijing,+86 018611440679, 18611440679@139.com*

Abstract: *With a multiple-mode receiver onboard, Chang'E-5 Test Vehicle (CE5T) was tested on its ability to receive the side-lobe weak signal of GNSS satellites. Results show that the on-board receiver can receive the signal, and its navigation and positioning for the large elliptical orbit phase using the GNSS satellite side-lobe signal are achieved. The possibility of receiving the side lobe signal of navigation satellites is analyzed theoretically; the received signal power and the number of satellites available in relation to the geocentric distance are studied, with the position dilution of precision also provided. The results indicate that the positioning ability can be achieved for orbits with geocentric distance less than 60000 km, provided the sensitivity of the receiver is better than -160 dBm. Additionally, both the navigation solution and pseudo-ranging are processed and analyzed, and the former is also employed to calculate the orbit. The noise level of the navigation solution is better than 10 m. Using differential pseudo-ranging, the noise level is approximately 8.5 m. 1 hour long data of the differential pseudo-ranging can achieve a 1 hour forecast orbit accuracy of better than 100 m, which will have to be obtained with long-arc data for the ground-based tracking stations.*

Keywords: *Chang'E-5 Test Vehicle (CE5T); Multi-mode Receiver; Orbit Determination; Accuracy Analysis*

1. Introduction

Launched on October 24, 2014, China’s Chang’E-5 Test Vehicle (CE-5T) is its fourth lunar probe to conduct atmospheric re-entry test on the capsule design planned for Chang’E-5 mission. With a multiple-mode receiver onboard, CE-5T was tested on its ability to receive the side-lobe weak signal of GNSS satellites.

In the early China’s lunar exploration mission, the tracking of the probes is based totally upon the Unified S/X-band and Very long base line interferometry. For Chang’E-1 and Chang’E-2, it required at least 10 hours to obtain an orbit with an accuracy of 100 m using both USB and VLBI tracking during the lunar transfer orbit[1,2].

GNSS has been widely used in the field of low orbit spacecraft navigation and has been applied to the study of the earth science[3]. The U.S. Goddard Space Center has tried to develop a GPS receiver for high orbit spacecraft[4], and successfully carried out a test to obtain the effective positioning data[5], and NASA has also developed a GPS receiver for lunar spacecraft, but did not carry out the experiments.

CE5T is a completely new attempt by carrying GNSS receiver. The successful acquisition of the pseudo range, phase data and satellite positioning results using the GNSS side lobe signals in the on-orbit flight is fully verified. In this paper, we deal with the GPS navigation solution and the pseudo range data, Carrier phase.

2. Visual analysis of navigation satellites

In the trial, the geocentric distance of CE5T ranges from 6500 km to 400000 km, which is far beyond the designed navigation ability of the current GNSS system[6,7]. For low orbit spacecraft, the receiver can receive the strong main lobe signals of GNSS satellites. As the geocentric distance increases to a certain extent, only the side lobe signal passing the earth can be picked up. Theoretically, the visibility of the navigation satellites can be calculated in two steps: (1) with the ideal condition that the navigation satellite antenna pointing to the center of the earth, the downlink signal lobe with a certain width, when the geocentric and CE5T with respect to the angle of navigation star than lobe angle, navigation star is invisible (2) when the angle is smaller than that of the lobe angle, if the navigation satellite and CE5T distance greater than navigation satellite geocentric distance and distance between the center of the guide vertical Hangxing and CE5T line is less than the radius of the earth, the satellite navigation is in the shadow of the earth, not visible (Figure 1). In addition, whether the receiver can receive the downlink signal depends on the transmit power, space environment and the capability of the receiver. Therefore, for this kind of long distance spacecraft, the ability of the receiver is an important factor to decide whether the receiver is capable of receiving side lobe signal.

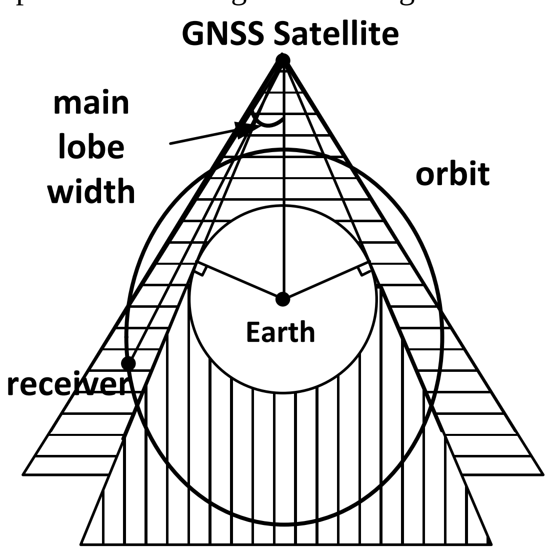

Figure 1. Navigation Satellite Availability

Depending on the power pattern of the GPS satellite, the signal of the main lobe is the most powerful with coverage of ±45 d[6], while that of the side lobe shows a decreasing tendency as the angle increases. With the CE5T receiver sensitivity between -140 dBm and -160 dBm, the different satellite availabilities are analyzed assuming a receiver sensitivity of -140 dBm, -150 dBm, and -160 dBm respectively. The availability status is classified into four categories: totally invisible, 1-3 satellites visible, 4-8 satellites visible, and 8 satellites and above visible. The geocentric distance is divided into 200000 km-segments in the 0-80000 km band. The satellite availability analysis results are given in figure 2: over 4 satellites are visible in the 0-20000 km segment for all three receiver sensitivities; for sensitivities better than -150 dBm, more than 4 satellites are visible under 40000 km, and a sentivity better than -160 dBm is needed for the 4-60000 km segments if 4 satellites availability is to be maintained. However, even though the receiving capability is enhanced with the improvement of the receiver performance, strong interferences resulted from multipath effects and background radiation place more stringent demands on the receiver performance and satellite equipment.

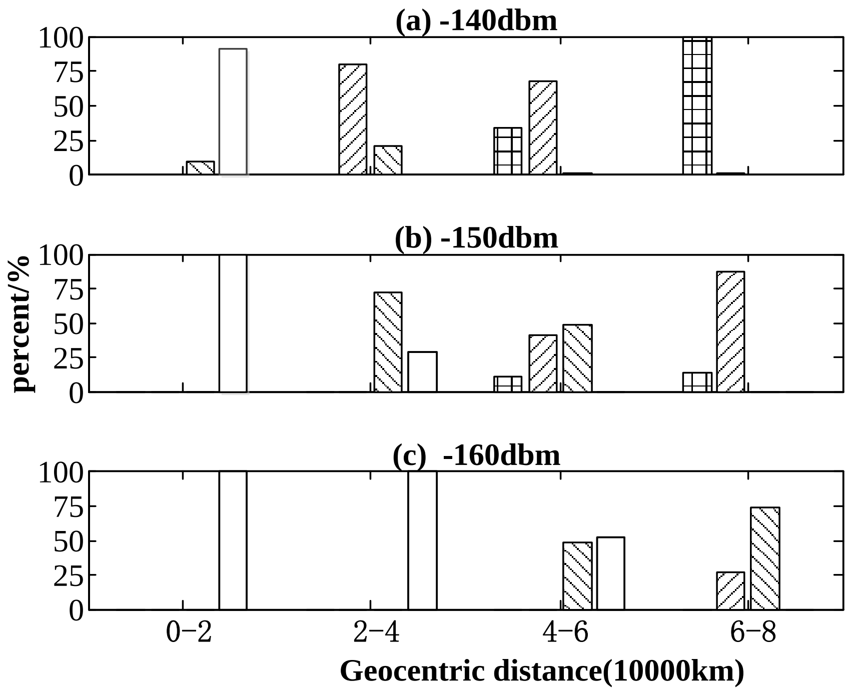

Figure 2. The number of visible satellites

3. Data analysis

Limited by the scheduling of the mission events, the onboard GNSS receiver was switched on during the beginning of the lunar transfer orbit phase and the end of the earth return phase. To ensure proper functioning of the GNSS receiver, an important constraint is that the maximum geocentric distance of CE5T be less than 60, 000 km. The GNSS receiver performed well in the two experiments (about 3 hours each time, 18:56~21:53 on October 23 and 18:55~21:56 on October 31). The GPS tracking data obtained in the two experiments are analyzed in this section.

3.1 Single point positioning analysis

Because differences exist between the actual values and the design targets regarding the satellite transmission power and the receiver performance, and also contributed by factors such as the actual working conditions of the instruments and equipment, the available navigation satellites actually received varies from the theoretical analysis. Figure 3 gives the actual status of visible satellites. During the two tests period, the number of visible satellite varied from 6 to 12, and the average visible satellites were 8.7 and 9.7 respectively. Using the pseudo range data obtained from the test, the 3D position accuracy factor is calculated. With the CE5T geocentric distance increasing, the PDOP value significantly becomes larger. It ranges from 1 to 20 in the transfer phase, and 40 to 0.5 in the return period.

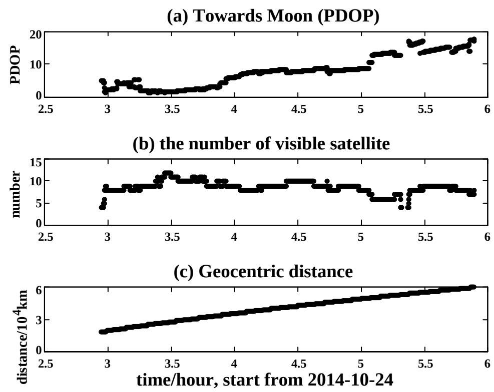

Figure 3. The variation of PDOP

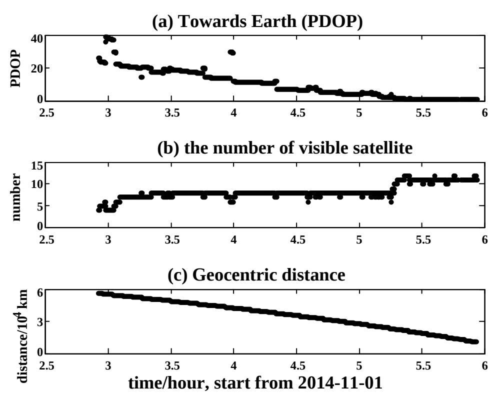

Figure 4. The variation of PDOP

Although the number of visible GPS satellites barely changes in the normal phase, the noise in the pseudo ranging data grows considerably as the geocentric distance increases, which leads to the increment in the PDOP. As a result, the accuracy of PPP decreases significantly. Due to the low stability of the GNSS receiver clock, calibrations are carried out as soon as the receiver clock error is larger than 1 ms. Using the PPP solution data, the position calculation as well as the receiver clock error calculation is conducted. A jump happens every 10 min clock error (Figure 5).

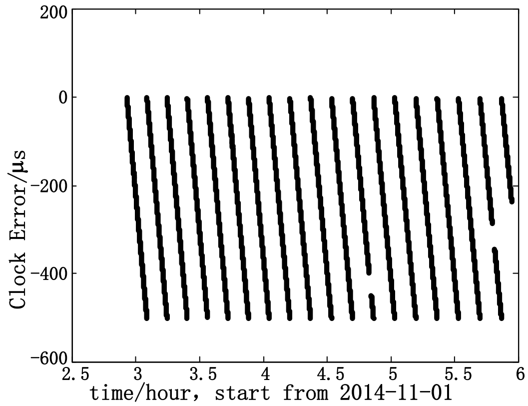

Figure 5. The variation of clock error

3.2 Navigation Solution Accuracy Evaluation

Since the receiver is featured with a filtering function, the generated navigation solution is not purely single point positioning. When the filter convergence is not stable, the single point positioning solution is generated; otherwise, the filtered result is generated. Both the PPP solution and the filtered results are called by the joint name of navigation solution in this paper. Relatively, the filtered results are more stable and more accurate than the PPP. But due to the fact that the receiver does not take into consideration the influences caused by orbit maneuvers and attitude controls, the disturbing forces have direct influences on the filtered results. Thus filtered results can not reflect the orbit maneuvers promptly, usually with delays. If the perturbations are significantly large, filtering restart might be resulted. Another issue with the filtering is that a certain amount of data is needed at the beginning for it to be stabilized. Unsatisfactory observation geometry may cause abnormal filtering convergence, which in the end may lead to unsatisfactory results even not as good as PPP.

In the return phase, the visible satellites are relatively less while the receiver is operating. With the receiving signal being weak, the pseudo-ranging data is of low quality. Thus abnormalities exist in the initial phase of filtering. Once, the filtering starts to converge, navigation solution would start to become normal, and its accuracy would also show superiority over that of the PPP.

The navigation solution can be used as an independent measuring source for orbit calculation. To some extent, the orbit determination residual can reflect the data quality. The navigation data obtained during the two working periods of the receiver are employed for orbit determination following the strategy in Table 1. Position and velocity are included as the solution parameters.

Table 1. Orbit Determination Strategy

Item	Description
Coordinate System	GCRS
Force Models	
	Earth
	Earth’s non-spherical gravitational perturbation (32×32)
	Sun, Moon
	Solar radiation pressure
Estimated Parameters	

Table 2 is the residual information in the orbit calculation using the navigation solution. The data shows no obvious systematic error, while discrepancies exist in each and every direction of the RMS. Compared with the DOP value, filtering significantly improved the positioning accuracy during the level flight phase. Larger error is indicated in the return phase than in the transfer phase, which is probably caused by the fact that the visible GPS satellites are more in terms of numbers in the initial stage of the transfer phase, and this contributed to good convergence for both PPP and filtering; while oppositely in the return phase, GPS satellite availability deteriorated in the early stage of filtering, and longer time is needed to obtain a stable orbit.

Table 2. statistic of the residuals

		X/m	Y/m	Z/m	POS/m
Towards Moon	Mean	0.16	0.24	0.10	0.31
	RMS	7.10	1.27	5.22	8.90
Towards Earth	mean	0.06	0.08	-0.08	0.13
	RMS	6.59	3.03	6.37	9.65

3.3 Orbit Calculation Based on Differential Pseudo-ranging

Pseudo-ranging data is directly obtained by the receiver, and can be used directly in the orbit determination. Considering the clock error drift is considerably large, we conducted satellite difference on the pseudo-ranging data to eliminate the receive clock error. The GPS ephemeris and clock error are needed for the orbit determination using differential pseudo-ranging data[8]. The satellite position at a given epoch is calculated using the Chebyshev polynomials to interpolate[9], and the clock error is obtained via linear interpolation.
Orbit determination is then conducted using the differentiated pseudo-ranging data following the same strategy in Table 1. Figure 6 is the residual depiction of the differential pseudo-ranging data.

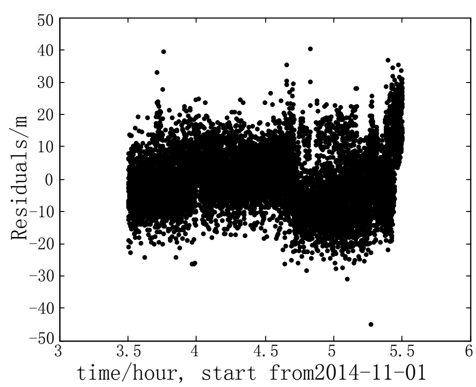

Figure 6. Residuals of differential pseudo range

CE5T is in a stable flying status during the period between the 5th trajectory correction maneuver and 5:48 on November 1. No attitude or orbit control is performed. In addition, in the same arc, ground-based tracking is in a satisfactorily good condition, which is jointly delivered by USB data from multiple stations and VLBI data from 6 base lines. The orbit thus calculated has an accuracy of better than 100 m. To test the quality of the receiver data, the orbit derived from ground-based station tracking data is used as reference and is compared with the orbit obtained using the pseudo-ranging data. Result shows that the 3 dimensional differences between the two types of orbit is less than 100 m. The orbit calculated from pseudo-ranging data is equally accurate with or even more accurate than the one using the ground station data.

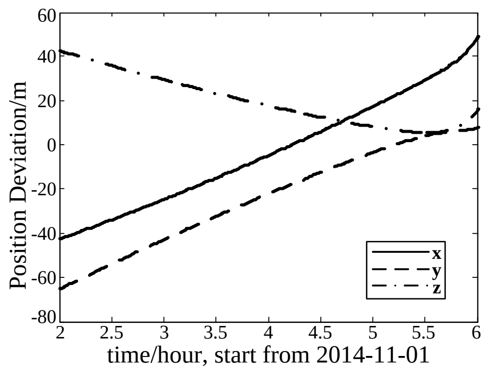

Figure 7. Comparison of ephemeris

3.4 Short Arc Orbit Determination Based on Pseudo-ranging Data

The receiver can acquire pseudo-ranging data from multiple GPS satellites at the same time. Compared with ground station data, pseudo-ranging data has a higher degree of observability, which makes it possible to obtain a relatively better accuracy even with short arcs. No attitude or orbit control being performed during the return phase paved the way for testing of the accuracy of the predicted orbit using short arcs. Taking the orbit calculated from all available GPS pseudo-ranging data in the return phase as a reference, the accuracy of the predicted orbit using short arcs is tested. Starting from 19:30, orbit calculation is carried out every 10 min, and is predicted every 1 hour. The predicted orbit is compared with the reference orbit to calculate the standard deviations in the orbit determination arc and in the prediction arc separately. In the orbit determination arc, all results in different arcs are better than 100 m. For arcs shorter than 30 min, the velocity deviations are relatively more significant at 5 cm/s. If the same accuracy of 100 m is to be achieved for 1 h predictions, a minimum of 30 min observation arc is required. Although short arcs can deliver good accuracies, the length of arcs is still an essential contributing factor in determining the accuracy of velocity. For transfer orbits with large eccentricity ratios like the one in question, velocity greatly affects the accuracy of the prediction orbit. Thus, over 1 h's data is required to achieve a good prediction accuracy using GPS data only, which, compared with relying solely on ground-based stations, is a great leap forward in terms of orbit accuracies.

Table 3. statistics of orbit errors

	Orbit determination		Orbit prediction with 1 hour	
Data arc /min	Position /m	velocity /(m/s)	position /m	Velocity /(m/s)
10	55.13	0.104	523.61	0.122
20	50.03	0.088	500.21	0.106
30	22.31	0.082	459.19	0.104
40	20.18	0.020	300.31	0.087
50	14.25	0.006	60.86	0.008

60	14.21	0.006	30.84	0.008

4. Conclusions

It is the first time that GNSS receiver is equipped on board the CE5T, and GPS navigation solution and pseudo-ranging data is successfully accessed in the test. This paper processed and analyzed the received data, which shows that the data is reliable. GPS data can be used as an independent measuring source to serve in the measurement and control system. Especially, for flying phases with no VLBI support, GPS data can effectively improve the orbit calculation and prediction accuracy. As an independent source, GPS data features the following advantages from our initial study in this paper:

(1) When the receive is working, the GPS data can be used to efficiently calculate the CE5T's orbit;

(2) For short arcs (less than 30 min), the GPS data can deliver good position accuracies, only with less satisfying velocity accuracy. If high accuracy is to be achieved for the prediction orbit, a minimum of 1 h observation arc is required, which is a significant improvement over using only the ground-based station data.

(3) Although the flying mission is on the moon exploration, all experiments are carried out in the transfer phase, during which the satellite is in a highly elliptical orbit, with the geocentric distant ranging from 6500 km to 60000 km. GPS can directly serve the medium and high earth orbit spacecraft.

5. References

[1] CHEN Ming, TANG Ge-shi, CAO Jian-feng, et al. Precision orbit determination of CE-1 lunar satellite [J]. Geomatics and Information Science of Wuhan University, 2011, 36(2): 212-217.

[2] CHEN Ming, ZHANG Yu, CAO Jian-feng, et al. Orbit determination and tracking technology of CE-2 satellite [J]. Chinese Science Bulletin, 2012, 57(9): 689-696.

[1] CHEN Ming, TANG Ge-shi, CAO Jian-feng, et al. Precision orbit determination of CE-1 lunar satellite [J]. Geomatics and Information Science of Wuhan University, 2011, 36(2): 212-217.

[2] CHEN Ming, ZHANG Yu, CAO Jian-feng, et al. Orbit determination and tracking technology of CE-2 satellite [J]. Chinese Science Bulletin, 2012, 57(9): 689-696.

[3] LUTHCKE S B, ZELENSKY N P, ROWLANDS D D, et al. The 1-Centimeter orbit: Jason-1 precision orbit determination using GPS, SLR, DORIS, and altimeter data [J]. Marine Geodesy, 2003, 26(3): 399-421.

[4] WINTERNITZ L, BAMFORD W A, HECKLER G W. A GPS receiver for High-Altitude satellite navigation [J]. IEEE Journal of Selected Topics in Signal Processing, 2009, 3(4): 541-556.

[5] AXELRAD P, BRADLEY B K, TOMBASCO J, et al. GEO satellite positioning using GPS collective detection[C]//23rd International Technical Meeting of the Satellites, 2010: 2076-2086.

[6] LORGA J M, SILVA P F, ANDREA D C, et al. GNSS sensor for autonomous orbit determination[C]//23rd International Technical Meeting of the Satellite Division of The Institute of Navigation． Portland, 2010: 2717-2731.

[7] YANG Y, LI J, XU J, et al. Contribution of the compass satellite navigation system to global PNT users [J]. Chinese SCI Bulletin, 2011, 56(26): 2813-2819.
[8] CAO Jian-feng, LI Xie, ZHANG Yu, et al. Spin effect correction method for spacecraft orbit measurement data [J]. Spacecraft Engineering, 2014, 23(3): 18-23.
[9] FENG Y, ZHENG Y. Efficient interpolations to GPS orbits for precise wide area applications [J]. GPS Solutions, 2005, 9: 273-282.