Research on Lunar Radio Measurements by Chang'E-3

Geshi Tang[1,2], Jianfeng Cao[1,2], Songtao Han[1,2], Songjie Hu[1,2], Tianpeng Ren[1,2], Lue Chen[1,2], Jing Sun[1,2], Mei Wang[1,2], Yifei Li[1,2], Li Li[1,2]

Abstract After the successful launch on December 2, 2013, the Chang'E-3 performed a soft landing on the lunar surface on December 14. The Chang'E-3 is designed to stand in place for more than one year, and it can transmit X-band signals when the transponder is switched on. With this signal ranging, doppler, carrier phase, and VLBI delay and delay rate can be acquired from ground TTC antennas and VLBI antennas. These techniques can be called Lunar Radio Measurement (LRM) collectively. By the LRM technique, more rich observations can be acquired nearly at the same time, so it should be more effective in contributing to space geodesy than LLR, which only provides ranging observations. To analyze the LRM technique, MEKAS (Moon Earth Kinematical Analysis Software) is developed, which can simulate all kinds of observations mentioned above, carry out covariance analysis, and determine the parameters including the CE'3 position on the lunar surface, ground site coordinates, UT1, EOP, and love numbers. A simulation is performed with MEKAS to analyze the ability of lunar lander positioning and estimation of earth rotation parameters. The results show that the LRM technique has wide prospects in terrestrial and lunar science.

Keywords Chang'E-3, Yutu Rover, X-band transponder, lunar radio measurements

1. National Key Laboratory of Science and Technology on Aerospace Flight Dynamics
2. Beijing Aerospace Control Center

1 Introduction

Lunar Laser Ranging (LLR) is a very important space geodetic technique in the sense that it can determine a huge number of parameters for lunar ephemerides, physical libration, the moon's interior structure, earth orientation parameters (EOP), and earth-moon dynamics. LLR can also be a powerful tool for testing Einstein's theory of general relativity. However, of all the ILRS observatories, only several sites are capable of carrying out Lunar Laser Ranging to retro-reflector arrays on the lunar surface, and 92% of the effective observations are concentrated in two sites (McDonald in the U. S. and Grasse in Europe). Furthermore, LLR observations are independent of the International Celestial Reference Frame (ICRF). It is difficult to tie lunar movement to the nearly inertial celestial reference frame. These deficiencies limit the increase of LLR's impact on terrestrial and lunar science. The successful launch of Chang'E-3 (CE-3) provides a new chance to break through these limitations. CE-3 was launched on December 2, 2013. It made a soft landing at the plains of Sinus Iridum (Rainbow Bay) successfully on the lunar surface on 14 December 2013. The lander will stand in place for at least one year. It is equipped with an X-band transponder, which can transmit an X-band signal to the ground when it is tracked by the Chinese Deep Space Network (CDSN). This signal not only can be utilized to provide range and Doppler observations by CDSN, but can also be received by widely distributed IVS antennas to provide VLBI observations. Combining these radio measurements from the earth to the moon, this technique can be called Lunar Radio Measurement (hereafter LRM) collectively. Based on these plentiful kinds of observations from CE-3, the LRM has at least four advantages as compared with

LLR. First, widely distributed IVS antennas provide a good PDOP (Position Dilution of Precision) factor. Secondly, VLBI is the unique technique to define inertial celestial frames; it can tie the lunar orbit to ICRF much more accurately. Third, range, doppler, carrier phase, time delay, and delay rate can be accessed at the same time, so it provides richer information than LLR. Fourth, an active radio signal can give a more intense observation. It is expected that the LRM will give more contributions to terrestrial and lunar science, especially in tying the earth-moon dynamical and kinematical frames. In view of this, it is of high interest to carry out research on the LRM utilizing the CE-3 signal.

2 Technique System

The LRM technique system includes two parts. One is a ground tracking and measurement system, and the other is a radio transponder on the spacecraft. The ground tracking and measurement system consists of CDSN, CVN, and BACC. The observations of CE-3 utilize the CDSN 66-m antenna at Jiamusi (JMS for short) and the 35-m antenna at Kashi (KSH for short). Two CDSN stations are responsible for receiving telemetry data and sending telecontrol instructions. They also provide range and range rate messages directly from baseband at the station, record raw data in the VSI or VSR formats, and transfer data to the correlation center at BACC for correlation of the time delays of the JMS—KSH baseline. Five CVN stations record raw data in Mark 5 and transfer the data to the SAO correlation center for correlation of the time delays of the SHESHAN (TIANMA) — BEIJING — URUMQI — KUNM stations' baselines. All CDSN stations and CVN stations deployed an H-atomic clock, a GNSS receiver, and a WVR to ensure high performance of observations. To expand the ground observation distribution, an intercontinental IVS baseline is needed to provide a better PDOP factor. But because the CE-3 transmits signals only when CDSN is tracking, IVS antennas in Asia, Europe, Africa, and Australia are good candidates. Furthermore, the CE-3's signal is much stronger than an extragalactic radio source, so it is not essential to use a large antenna; perhaps a 12-m VGOS antenna is a better candidate. To test the performance of a small antenna, an old 12-m antenna at BACC/AFDL was reformed to receive the CE-3 signal. Because the LNA and the first level down-conversion are placed more than 60 meters away from the control room where the Rubidium atomic clock (HP5156) is placed, Active Phase Compensation Technology (APCT) was designed to ensure the down-conversion and to ensure that the A/D sampler gets stable LO when the local oscillation (LO) transfers from HP5156 to down-conversion and to the A/D sampler by optical fiber, By the APCT, the LO phase stability can be higher than 0.05 rad. With the ground antenna, the correlation center, and the CE-3 spacecraft, both the lander and the rover can be utilized as radio beacons on the lunar surface. These radio beacons are different from extragalactic radio sources in the follow aspects: (1) the lander and the rover can only work during the lunar day; (2) there are several single frequency signals (DOR and range tone) coherent with the uplink signal and with the high frequency stability($\sim$10-14) when the ground antenna's main carrier is uploaded to the lander; (3) the lander sends a wideband data transmission signal or DOR and range tone only when BACC gives instructions, and (4) the rover sends its telemetry signal all the time during the lunar day.

3 Experiments and Performance

By different tracking modes in the CE-3 mission, different observations can be achieved: (1) from baseband in the CDSN station, the range and the range rate can be acquired; (2) from the correlation center, the time delay and the delay rate of different baselines can be acquired; (3) from the correlation center, when the SBI mode is utilized, the difference in the time delay and the delay rate between the lander and the rover can be acquired, and (4) the VSI raw data in the digital back-end and the carrier phase can be extracted, regardless of the baseband; if the ambiguities can be fixed, a higher phase range can be acquired. To get the time delay and the delay rate, the raw data recorded at different stations must be transferred to the correlation center. In the correlation center, a correlator must be deployed. With the development of the computer technique, the software correlator has become more and more popular. The BSCS (BACC Software Correlator System) is developed with the basic principle of DiFX at BACC. The software correlator has the ability to process VLBI data for both spacecraft navigation and quasars. The software is written modularly in the C programming language. The correlator is operated by shell script and is intended to run in clusters of the multiprocessor shared-memory machine. Figure 1 gives the performance of all kinds of observations in CE-3 tracking measurements.

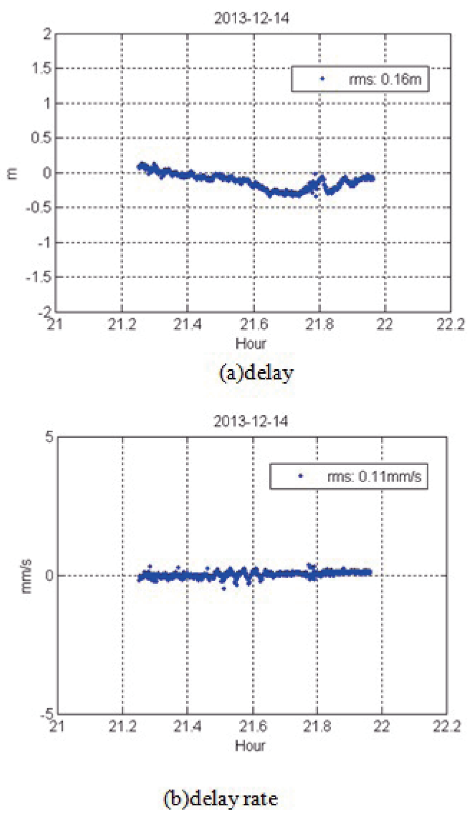

Fig. 1 Delta-DOR tracking observable accuracy. The random error is about 0.5 ns and 0.33 ps/s.

It shows that the Delta-DOR tracking observable accuracy is about 0.5 ns and 0.33 ps/s separately; SBI tracking shows the excellent agreement between the observation and the status of the rover and the lander. The movement of the rover can be identified to the order of 1 mm with SBI tracking data. Figure 3 also shows that the accuracy of the carrier phase can be better than 0.1 radians for the CDSN and 0.5 radians for the 12-m antenna, which means that an accuracy of 1-2 mm for phase ranging can be obtained if the ambiguity can be fixed.

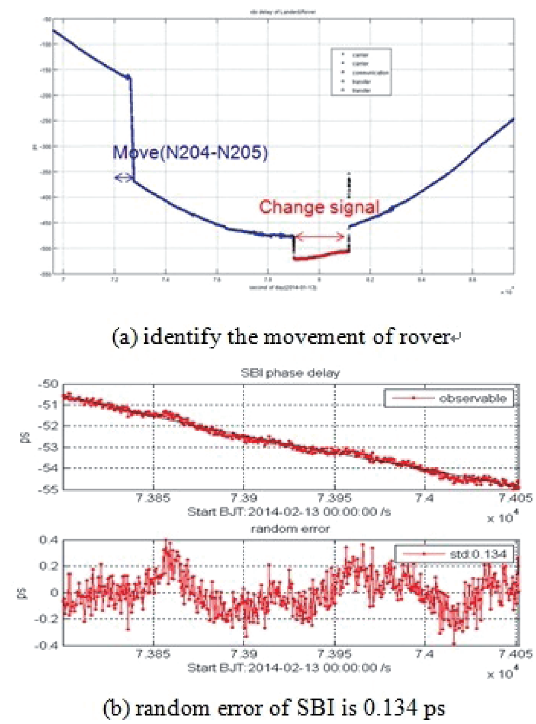

Fig. 2 SBI observing results.

4 Scientific Prospects

Now, with the radio measurement of the CE-3 lander, we can get a high precision and denser earth-moon observation ranging, and a greater contribution to terrestrial and lunar science is expected from the CE-3 program. To analyze the proper lunar science from the Lunar Radio Measurement technique, the MEKAS (Moon-Earth Kinetics Analysis Software) software is developed at the BACC. The software's main component is a collection of modules coded in FORTRAN. MEKAS has four main basic functions: observation simulation, generation of partial derivatives, estimation of uncertain parameters, and covariance analysis. The observations that can be processed in MEKAS include two-way/three-way Ranging and Doppler, VLBI delay and rate, DOR and DOD, Lunar laser Ranging, etc. The parameters that can be estimated or considered include locations of lunar landers or reflectors, station coordinates, earth rotation parameters, observation bias, and lunar love numbers, and the selection and settings of the parameters are flexible. The input to MEKAS is a card file named 'mmekas.dat'. In the input card file,

Table 1 The positioning accuracy of the lunar lander without IVS stations.

days	duration	case 1 std(x)	case 1 std(y)	case 1 std(z)	case 2 std(x)	case 2 std(y)	case 2 std(z)
1	1 hour	19.8951 m	0.9469 m	0.9547 m	28.2151 m	9.3839 m	9.5947 m
1	3 hour	19.4784 m	0.5687 m	0.9371 m	40.8174 m	6.9534 m	9.7245 m
2	1 hour	17.6182 m	0.7441 m	0.6484 m	42.3477 m	11.5982 m	8.1453 m
2	3 hour	12.0579 m	0.3046 m	1.2913 m	43.2007 m	8.4646 m	6.3751 m
5	1 hour	6.6759 m	0.5335 m	0.7352 m	46.9875 m	5.9377 m	13.7138 m
5	3 hour	3.8214 m	0.1899 m	0.3807 m	23.6102 m	7.2608 m	6.8793 m

Table 2 The positioning accuracy of the lunar lander with joint tracking from IVS stations.

days	duration	case 1 std(x)	case 1 std(y)	case 1 std(z)	case 2 std(x)	case 2 std(y)	case 2 std(z)
1	1 hour	30.9289 m	0.6526 m	3.3695 m	37.0099 m	0.80756 m	4.0622 m
1	3 hour	15.7896 m	0.3161 m	1.7339 m	21.5096 m	0.44933 m	2.4005 m
2	1 hour	7.0289 m	0.1572 m	0.7977 m	7.3167 m	0.20823 m	0.8411 m
2	3 hour	4.05749 m	0.0985 m	0.4622 m	4.5024 m	0.18013 m	0.5292 m
5	1 hour	0.6576 m	0.0881 m	0.0614 m	0.9487 m	0.1439 m	0.1042 m
5	3 hour	0.4142 m	0.0569 m	0.0365 m	0.8968 m	0.1409 m	0.0918 m

Table 3 The uncertainty of EOP estimation with the lunar lander.

Tracking arc	case 1 std(xp)	case 1 std(yp)	case 1 std($UT1-UTC$)	case 2 std(xp)	case 2 std(yp)	case 2 std($UT1-UTC$)
1 hour	0.22 mas	0.28 mas	0.05 ms	0.38 mas	0.41 mas	0.22 ms
2 hour	0.17 mas	0.19 mas	0.03 ms	0.37 mas	0.28 mas	0.20 ms
3 hour	0.17 mas	0.16 mas	0.03 ms	0.36 mas	0.20 mas	0.15 ms
4 hour	0.16 mas	0.13 mas	0.02 ms	0.35 mas	0.18 mas	0.09 ms

we can set the following items: (1) the location and the uncertainty of the lunar landers or lunar laser reflectors; (2) an observation to be processed in MEKAS and the weight settings; (3) the parameters to be estimated or considered in MEKAS, and (4) one or more observation files. With MEKAS, we performed some analysis. The following tables show the possible positioning accuracy of the lunar lander based upon the tracking data from CDSN and CVN. Because it is hard to determine the tracking data bias each pass in the positioning performance, a priori information for the elevation of the lunar lander with an uncertainty of ten meters is considered. Without regard to the uncertainty of the tracking station coordinates, the accuracy of the positioning gets better as the tracking arc increases. As the tracking data reaches five days, the results would be at a level of 1 m. Once an uncertainty of 15 cm for the tracking stations is taken into account, the accuracy may be decreased by ten meters. Table 1 lists the positioning accuracy of the lunar lander. Case 1 considers only the observation noise, while Case 2 also considers the uncertainty of the tracking station coordinates. With the assistance of IVS, VLBI stations in the southern hemisphere may join the tracking of the Chang'E-3 lunar lander. A simulation is performed with tracking stations from CDSN, CVN, and IVS. Table 2 shows the possible positioning accuracy of CE-3 with the joint tracking from IVS tracking stations. Case 1 and Case 2 are the same as in Table 1. The LLR retroreflector array principal axis coordinates were determined during the solution leading to development ephemerides. Comparing the LLR retroreflector coordinates from DE421 and DE430, there is also a shift of 1 m along the x axis. The results mean that the accuracy of the lunar lander is at the same level as that of the retroreflector, and the lunar lander can be treated as a lunar control point. Normally, the EOP is determined at the IERS Earth Orientation Center in the form of combined solutions derived from individual series, and the results are published in a bulletin with a delay of thirty days until the date of publication. The accuracy of polar motion is about 0.1 mas, and that of UT1 is 0.02 ms. Once the coordinates of the lander are determined precisely, it is possible to get the same accuracy as IERS distributed for EOP and UT1. Table 3 gives the possible accuracy for EOP estimation with a 1 m uncertainty of the lunar lander coordinates. Case 1 only considers the observation noise, while Case 2 considers observation noise and an uncertainty of 1 m for the lunar lander coordinates. In the construction of DE430,

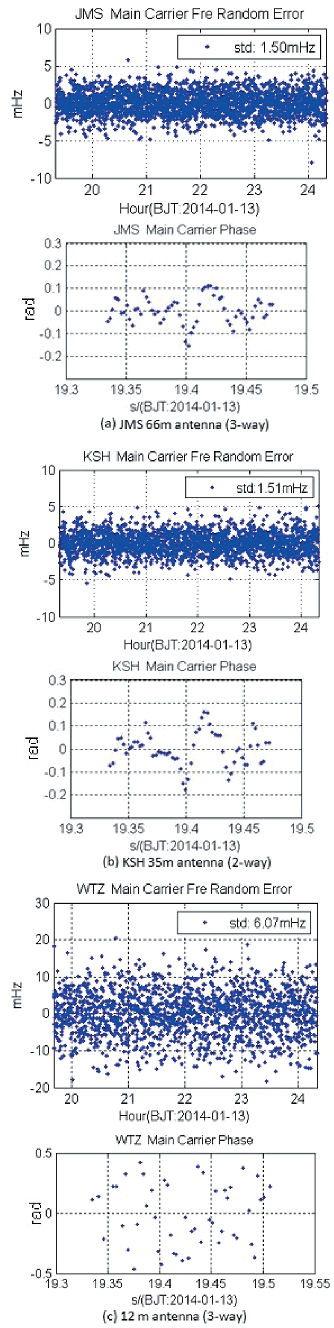

Fig. 3 Doppler and carrier phases at different antennas.

Lunar Love number h2 was estimated, while k2 was set equal to a GRAIL-determined value. The lunar displacement Love numbers from the solution leading to DE430 are h2=0.0476 and l2=0.0107. Comparing the h2 from DE421 and DE430, there is a shift of 0.01. With long term tracking of the lunar lander, it is also possible to estimate lunar love numbers. Table 4 gives the results from covariance analysis for the estimation of lunar love numbers. As the tracking arc reaches 30 days, the uncertainty is about 0.0053 for h2 and 0.0023 for l2 respectively. The LRM technique acting on the lunar lander can contribute to the estimation of lunar love number h2.

Table 4 The uncertainty of lunar love number estimation.

Arc	Lunar love numbers std($h2$)	Lunar love numbers std($l2$)
1 day	4.1576	5.7142
7 days	0.0355	0.0080
15 days	0.0123	0.0053
30 days	0.0053	0.0023

5 Summary

The CE-3 lander and the rover stand in place on the lunar surface, sending radio signals. After the positioning accuracy of the lunar lander improves to the sub-meter level, the lander can be utilized as a very good radio beacon to contribute to lunar and terrestrial science as LLR reflectors. The analysis results from MEKAS show that the current accuracy of radio measurements is expected to ensure one meter level positional precision of the CE-3 lander if the observing arc is enough, so it can be a good control point as a laser reflector; as a highly precise positional radio beacon on the moon's surface, its signal can be received by ordinary IVS antennas—even a 12-m antenna, when CDSN tracks the lander. Therefore, it is convenient and cheap to expand the ground observation distribution, a target that the LLR community will always be eager to pursue. This is expected to contribute more to terrestrial and lunar science; the geodetic VLBI technique's observation of quasars provides highly accurate positions for the ICRF, EOP, site coordinates etc. With the LRM technique's millimeter observational precision, if it is used with the LLR technique, it is possible to make great progress in many aspects of terrestrial and lunar science including lunar ephemerides, lunar physics, the moon's interior, various reference frames, earth orientation parameters, earth-moon dynamics, and testing Einstein's theory of general relativity.