Research on Lunar Radio Measurement by Chang'E-3

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Abstract: *The Chang'E-3 has successfully landed softly on the lunar surface on December 14, 2013, which was designed for scientific observations in place for more than one year with transmitting X-band signals. The Lunar Radio Measurements (LRM), including the ranging, Doppler, carrier phase, VLBI delay and delay rate can be acquired from ground TT&C antennas and VLBI antennas, which will greatly contribute to space geodesy than LLR that only provides the ranging observation. In this paper, the MEKAS (Moon Earth Kinematical Analysis Software) is developed to simulate all kinds of observations mentioned above, carry out covariance analysis and determine the parameters, including CE-3 position on the lunar surface, ground site coordinates, EOP and love number. A simulation is performed with MEKAS to analyze the ability of lunar lander positioning and estimation of Earth rotation parameters. The results show that LRM technique has wide prospects in Earth and lunar science.*
Keywords: *Chang'E-3, Yutu Rover, X-band transponder, Lunar Radio Measurement*

1. Introduction

Lunar Laser Ranging (LLR) is very important in space geodetic technique in the sense that it can determine a huge number of parameters for lunar ephemeris, physical libration, 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 (J. G. Williams et al., 1996). 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% effective observations is concentrated in two sites (McDonald in US and Grasse in EUROP) (http://ilrs.gsfc.nasa.gov). Furthermore, LLR observation in some sense is independent of International Celestial Reference Frame (ICRF). W. M. Folkner had endeavored to tie the extragalactic-planetary frame and presented an indirect determination by combining LLR and VLBI observations (W. M. Folkner et al., 1994). But it is also very difficult to tie these two frame. These two deficiencies limit LLR increasing its' impact in earth and lunar science (J. G. Williams et al, 2004). At Apollo era, a program of ALSEP-Quasar VLBI has been carried out for the first time (M. A. Slade, et al., 1977). Nearly 40 years later, the successful deployment of the Chang'e-3 Lander on the moon with its X-band transponder has opened a new window for VLBI observations of the moon. The VLBI observations of the moon provides a direct opportunity to tie the extragalactic-planetary frame and wide distribution of IVS station provides a new chance to break through the limitations that LLR confronted.
CE-3 was launched on December 2, 2013. It makes a soft landing at the plains of Sinus Iridum (Rainbow Bay) on lunar surface on 14 December 2013 successfully. The lander will stand in place for at least one year. It is equipped with an X-band transponder, which can transmit X-band signal to the ground when it

is tracked by 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 wide distributed IVS antenna to provide VLBI observations. Combining these radio measurements from 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, LRM has at least four advantages as compared with LLR. Firstly, wide distributed IVS antenna provides good PDOP (Position Dilution of Precision) factor. Secondly, VLBI is the unique technique to define inertial celestial frame, it can tie the lunar orbit to ICRF much more accurately. Thirdly, range, Doppler, Carrier phase and time delay, delay rate can be acquired at the same time, it provides more rich information than LLR which can only acquire range observation from station to retro-reflector. Fourth, active radio signal can give more intensive observation than LLR which can only acquire one normal point data every 10~20 minutes. It is expected that LRM will give more contributions to earth and lunar science, especially in tying earth-moon dynamical and kinematical frame. In view of this, it is of high interesting to carry out a research on LRM utilizing CE-3 signal.

2.Technique System

The LRM technique system includes two parts, one is ground tracking and measurement system, and the other is radio transponder on the spacecraft. The ground tracking and measurement system consists of CDSN, CVN and BACC. The observations in CE-3 utilize CDSN 66-m antenna in Jiamusi (JMS in brief) and 35-m antenna in Kashi (KSH in brief). Two CDSN station are responsible for receiving telemetry data and sending telecontral instruction, they also provide range, range rate message directly from baseband in the station, record raw data in VSI or VSR format and transfer to correlation center in BACC to correlate to get time delay of JMS-KSH baseline. Five CVN stations record raw data in MARK5 and transfer to correlation center in SAO to correlate to get time delay of SESHAN (TIANMA) – BEIJING – URUMUQI - KUNM baseline. All CDSN station and CVN station deployed H-atomic clock, GNSS receiver and WVR to ensure high performance of observations.

To expand ground observe distribution, intercontinental IVS baseline is needed to provide better PDOP factor. But because CE-3 transmits signal only when CDSN is tracking, IVS antenna in Asia, Europe, Africa and Australia is good candidates. Furthermore, CE-3's signal is much more stronger than extragalactic radio source, it is not essential to use large antenna, maybe 12m VGOS antenna is better candidates.

To test the performance of small antenna, an old 12-m antenna in BACC/AFDL were reformed to receive CE-3 signal. Because the LNA and first level down-conversion is placed more than 60 meters away from control room where Rubidium atomic clock (HP5156) is placed, when the local oscillation (LO) transfer from HP5156 to down-conversion and to A/D sampler by optical fibre, an Active Phase Compensation Technology (APCT) were designed to ensure the down-conversion and A/D sampler get the stable LO. By APCT, phase stability of LO can be higher than 0.05 rad.

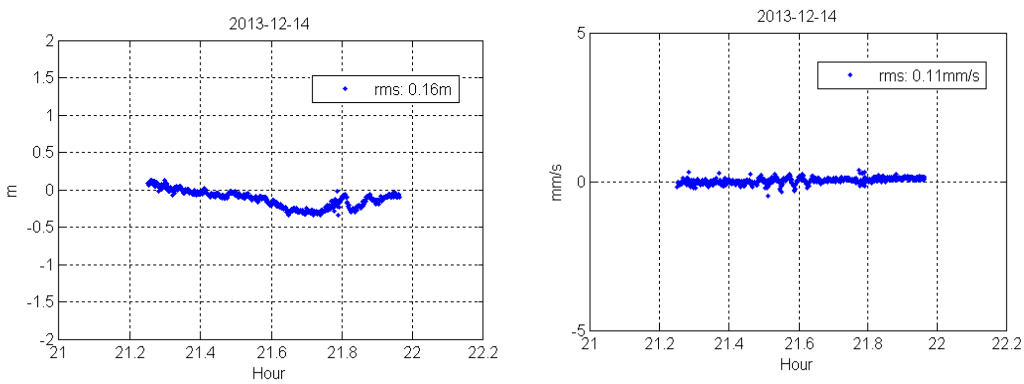
With these ground antenna and correlation center, CE-3 spacecraft both lander and rover can be utilized as radio beacon on the lunar surface. These radio beacon is different from extragalactic radio source in follow aspect: (1) only in moon day lander and rover can work; (2)there are several single frequency signal(DOR & range tone) coherent with uplink signal with high frequency stability(~10-14) when ground antenna upload main carrier to the lander; (3) lander send wideband data transmitting signal or DOR & range tone only when BACC give instructions; (4) rover sends its' telemetry signal all the time in moon day.

3. Experiments and performance

By different tracking mode in CE-3 mission, different observations can be get: (1) from baseband in CDSN station, range and range rate can be get $(\rho, \dot{\rho})$; (2) from correlation center time delay and delay rate of different baseline can be get $(\tau, \dot{\tau})$; (3) from correlation center, when SBI mode is utilized, difference time delay and delay rate between lander and rover can be get $(\Delta\tau, \Delta\dot{\tau})$; (4) no matter from baseband or from VSI raw data in Digital Backend, carrier phase can be extracted, if the ambiguities can be fixed, higher phase range can be get.

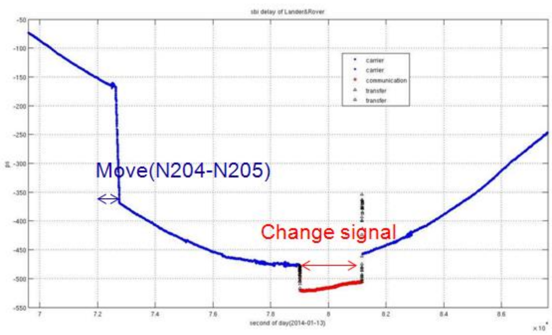
To get time delay and delay rate $(\tau, \dot{\tau})$, the raw data recorded in different station must be transferred to correlation center. In correlation center, there must deploy correlator. With the development of computer technique, software correlator is more and more popular. BSCS(BACC Software Correlator System) is developed with the basic principle of Difx in BACC. The software correlator has the ability of VLBI data processing both for spacecraft navigation and quasar. The software is written modularly in the C programming language. The correlator is operated by shell script and intended to run in clusters of multiprocessor shared-memory machine.

Following figure gives the performance of all kinds of observations in CE-3 tracking measurement.



(a)delay (b)delay rate

Figure 1. Delta-DOR tracking Observable Accuracy, the random error is about 0.5ns and 0.33ps/s corresponding $(\Delta\tau, \Delta\dot{\tau})$



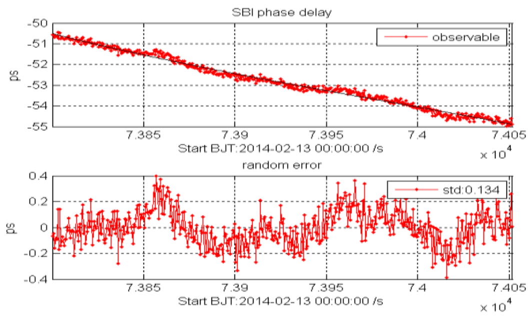
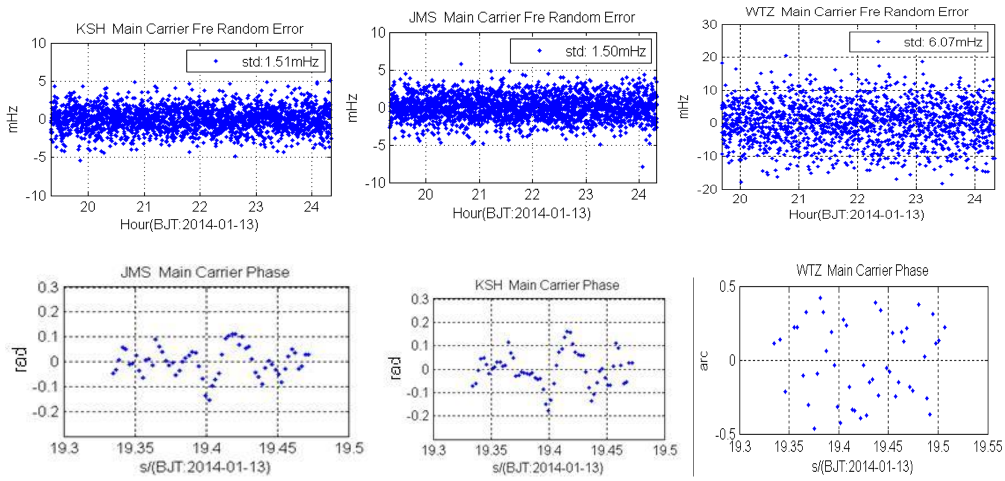


Figure2. (a)SBI observing identify the movement of rover; (b)random error of SBI is 0.134 ps

It shows the accuracy of $(\tau, \dot{\tau})$ is about 0.5ns and 0.33ps/s separately; $(\Delta\tau, \Delta\dot{\tau})$ of SBI tracking shows the excellent agreement between observable and status of the rover and lander. The movement of the Rover with the order of 1 mm can be identified with SBI tracking data.



(a) KSH 35m antenna (2-way) (b) JMS 66m antenna (3-way) (c) 12 m antenna (3-way)

Figure 3. Doppler and carrier phase in different antenna

Fig3 also shows that the accuracy of carrier phase can be better than 0.1 radium for CDSN and 0.5 for 12-m antenna, which means an accuracy of 1-2 mm for phase ranging can be obtained if the ambiguity can be fixed.

4. Scientific prospects

Now with Radio Measurement of CE-3 lander, we can get a high precision and more densification observation ranging from earth to moon, it is expected more contribution to earth and lunar science from CE-3 program.

To analyze the proper lunar science from Lunar Radio Measurement technique, the software named MEKAS (Moon-Earth Kinetics Analysis Software) is developed at BACC. The main component of the software is a collection of modules, which are coded in FORTRAN. MEKAS has the four main basic functions: observation simulation, partial derivatives generation, 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, et. al. The parameters that can be estimated or considered includes 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 of MEKAS is an input card file named 'mmekas.dat'. In the input card file, we can set the following items: (1) Location and the uncertainty of the lunar landers or lunar laser reflectors. (2) Observation that would be processed in MEKAS and the weight settings. (3) The parameters would be estimated or considered in MEKAS. (4) One or more observation files.

With MEKAS, we performed some analysis. The following table shows the possible positioning accuracy of 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 lunar lander with the uncertainty of 10 m 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 5 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 the positioning accuracy of the lunar lander

Tracking arc		Case 1			Case 2		
days	duration	$\sigma_x(m)$	$\sigma_y(m)$	$\sigma_z(m)$	$\sigma_x(m)$	$\sigma_y(m)$	$\sigma_z(m)$
1	1 hour	19.8951	0.9469	0.9547	28.2151	9.3839	9.5947
	2 hour	19.7739	0.6906	0.9791	29.8690	7.9650	9.4639
	3 hour	19.4784	0.5687	0.9371	40.8174	6.9534	9.7245
	4 hour	18.8515	0.4791	0.86487	57.5364	6.2989	10.3120
2	1 hour	17.6182	0.7441	0.6484	42.3477	11.5982	8.1453
	2 hour	14.7238	0.4453	1.5630	49.9368	9.8352	7.1615
	3 hour	12.0579	0.3046	1.2913	43.2007	8.4646	6.3751
	4 hour	9.9867	0.2261	1.0783	32.8026	7.5073	5.5522
5	1 hour	6.6759	0.5335	0.7352	46.9875	5.9377	13.7138
	3 hour	3.8214	0.1899	0.3807	23.6102	7.2608	6.8793
	4 hour	2.1843	0.1872	0.3293	15.3423	6.2302	4.3312

Case 1 represents only the observation noise is taken into account, Case 2 considers not only the observation noise, but also the uncertainty of the tracking station coordinates.

With the assistance of IVS, the Position Dilution of Positioning(PDOP) can be improved greatly. A Covariance analysis is performed with tracking stations from CDSN, CVN and IVS station (Onsala / Wettzell / NyAlesuna / HartRAO / Syowa / Hobart). Table 2 shows the possible positioning accuracy of CE-3 with the joint tracking from IVS tracking stations.

Table2 the positioning accuracy of the lunar lander

Tracking arc		Case 1			Case 2		
days	duration	$\sigma_x(m)$	$\sigma_y(m)$	$\sigma_z(m)$	$\sigma_x(m)$	$\sigma_y(m)$	$\sigma_z(m)$
1 day	1 hour	30.9289	0.6526	3.3695	37.0099	0.80756	4.0622
	2 hour	20.9074	0.4395	2.2873	27.4372	0.60765	3.0407
	3 hour	15.7896	0.3161	1.7339	21.5096	0.44933	2.4005
	4 hour	12.6254	0.2283	1.3889	17.7985	0.31904	1.9850
2 days	1 hour	7.0289	0.1572	0.7977	7.3167	0.20823	0.8411
	2 hour	5.0524	0.1184	0.5738	5.4678	0.19028	0.6344

	3 hour	4.0574	0.0985	0.4622	4.5024	0.18013	0.5292
	4 hour	3.3544	0.0829	0.3839	3.7474	0.16241	0.4471
3 days	1 hour	3.6094	0.1536	0.4175	3.8292	0.20137	0.4481
	2 hour	2.6498	0.1140	0.3050	3.0000	0.18047	0.3476
	3 hour	2.1781	0.0935	0.2505	2.5838	0.16876	0.2977
	4 hour	1.8492	0.0783	0.2136	2.2257	0.15319	0.2599
4 days	1 hour	2.3081	0.1490	0.2669	2.5501	0.19692	0.2988
	2 hour	1.7157	0.1116	0.1963	2.1059	0.17796	0.2395
	3 hour	1.4304	0.0922	0.1626	1.9028	0.16697	0.2094
	4 hour	1.2328	0.0775	0.1403	1.7040	0.15142	0.1858
10days	1 hour	0.6576	0.0881	0.0614	0.9487	0.1439	0.1042
	2 hour	0.4868	0.0664	0.0442	0.8902	0.1398	0.0959
	3 hour	0.4142	0.0569	0.0365	0.8968	0.1409	0.0918
	4 hour	0.3691	0.0506	0.0318	0.8969	0.1391	0.0876

Case 1 and case 2 are the same as that 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 means that the accuracy of the lunar lander is at the same level as the retroreflector, and the lunar lander can be treated as a lunar control point.

Normally EOP is determined at the IERS Earth Orientation Centre in the form of combined solutions derived from individual series, and the results are published in Bulletin with a delay of thirty days till the date of publication. The accuracy of polar motion is about 0.1mas and that of UT1 is 0.02ms. Once the coordinate of the lander is determined precisely, it is possible to get the same accuracy as IERS distributed for EOP, UT1. Table 3 gives the possible accuracy for EOP estimation with a 1 m uncertainty of lunar lander coordinates.

Table 3 the uncertainty of EOP estimation with lunar lander

Tracking arc	Case 1			Case 2		
	σ_{xp} (mas)	σ_{yp} (mas)	$\sigma_{\text{UT1-UTC}}$ (ms)	σ_{xp} (mas)	σ_{yp} (mas)	$\sigma_{\text{UT1-UTC}}$ (ms)
1 hour	0.22	0.28	0.05	0.38	0.41	0.22
2 hour	0.17	0.19	0.03	0.37	0.28	0.20
3 hour	0.17	0.16	0.03	0.36	0.20	0.15
4 hour	0.16	0.13	0.02	0.35	0.18	0.09

Case 1 only considers the Observation noise, case 2 considers observation noise and the uncertainty of 1m for the lunar lander coordinates.

In the construction of DE 430, Lunar Love number h2 was fit while k2 was set equal to a GRAIL-determined value. The lunar displacement Love numbers from the solution leading to DE430 are $h_2 = 0.0476$, $l_2 = 0.0107$. Comparing the h2 from DE421 and DE430, there is a shift of 0.01. With long term tracking of 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 lunar lander can contribute to the estimation of lunar love number h2.

Table 4 the uncertainty of lunar love numbers estimation

Tracking arc	Lunar love numbers	
	σ_{h2}	σ_{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. Conclusion

CE-3 lander and rover stand in place on the lunar surface, sending radio signal. After the positioning accuracy of lunar lander is improved to sub-meter level, the lander can be utilized as a very good radio beacon to contribute to lunar and earth science as LLR reflectors.

The analysis results from MEKAS show that the current accuracy of radio measurement which include $(\rho, \dot{\rho})$ and $(\tau, \dot{\tau})$ is expected to ensure one meter level positional precise of CE-3 lander if observing arc is enough, so it can be a good control point as laser reflector;

As a high positional precise radio beacon on the moon surface, its' signal can be received by ordinary IVS antenna even a 12m antenna when CDSN tracks the lander. So it is convenience and cheap to expand the ground observe distribution which is the target that LLR technique always be eager to pursuit, this is expected to contribute more to earth and lunar science;

The geodetic VLBI technique with $(\tau, \dot{\tau})$ observing to quasar provides high accurate positions of the ICRF, EOP, site coordinates and et. al., By LRM technique with observation not only $(\tau, \dot{\tau})$ but also $(\rho, \dot{\rho})$ with millimeter precise, and if it is cooperated with LLR technique, it is possibility to make great progress in many aspects on earth and lunar science include lunar ephemeris, lunar physics, the Moon’s interior, various reference frames, Earth orientation parameters, Earth-Moon dynamics and the testing for Einstein's theory of general relativity.

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