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Research Article

Lunar Radiometric Measurement Based on Observing China Chang'E-3 Lander with VLBI—First Insight

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China Chang'E-3 performed soft landing at the plains of Sinus Iridum on lunar surface on December 14th 2013 successfully; it opened a new window for observing lunar surface with radiometric tracking which many lunar scientific researchers always pursue for. Since July 2014, OCEL (Observing Chang'E-3 Lander with VLBI) project has been conducted jointly by IVS (International VLBI Service of Geodesy and Astrometry) and BACC (Beijing Aerospace Control Center), a global IVS R&D network augmented with two China Deep Space Stations configured for OCEL. This paper presents the current status and preliminary result of the OCEL and mainly focuses on determination of the lander position, which is about 7 meter in height and 14 meter in plane of lunar surface with respect to LRO (Lunar Reconnaissance Orbiter). Based on accuracy analysis, further optimized OCEL sessions will make use of this target-of-opportunity, the Chang'E-3 lunar lander, as long as it is working. With higher accurate radiometric observables, more prospective contribution to earth and lunar science is expected by combining with LLR.

1. Introduction

The Moon has always been a prime object of human space exploration, as it holds the distinctions of being the nearest remote celestial object to the earth. Since the first successful spacecraft "lunar 2" reached lunar surface by Soviet Union in 1959, more than 100 missions have been undertaken to research the Moon [2]. In 1969, the Apollo program started a new era for studying the Moon, such as determining parameters of the lunar orbit, physical librations, interior structure, and Earth-Moon dynamics [3]. Since then, LLR (Lunar Laser Ranging) Operation has been conducted to the retroreflector arrays at the Apollo 11, 14, and 15 sites plus the French-built reflector on the Soviet Lunokhod 1 and 2. Two sites, McDonald in USA and Grasse in France, conducted most LLR [4]; especially, Grasse site can even do LLR in day time and in new moon as well as in full moon days. The LLR data collected has significantly contributed to a large scientific domain [5–7].

LRM (Lunar Radiometric Measurement), including Ranging, Doppler tracking and VLBI (Very Long Baseline Interferometry), is another technique conducted in the Moon research. Based on ranging measurement, the LLR data is more sensitive to most of the dynamics, especially the orbital motion of the moon. While earth-based VLBI data has the potential to tie lunar movement to the inertial celestial reference frame [8]. In fact, VLBI measurement to radio beacon on lunar surface existed for less than five years totally in the nearly 50-years-long history of LLR. Though many suggestions and proposals were appealed [9, 10], none came into application until China Chang'E-3 Lander landed on plains of Sinus Iridum of lunar surface on Dec 14th, 2013.

In this paper, we will give an introduction and preliminary analysis of the first LRM with China Chang'E-3 Lander. The paper is organized as follows: Section 2 gives a review of LRM in history; introduction of OCEL (Observing Chang'E-3 Lander with VLBI) project is given in Section 3;

Section 4 discusses the preliminary result of OCEL; based on the analysis and discussion, conclusion and suggestions are given in Section 5.

2. LRM in History

The first earth-based radiometric measurement to lunar lander could be recalled back to nearly 50 years ago, the Apollo era [16]. NASA (National Aeronautics and Space Administration) designed and launched the Apollo program to land humans on the Moon and bring them safely back to the earth [17]. With five of the successful Apollo missions, ALSEP (Apollo Lunar Surface Experiments Package) was carried out, which was designed to continuously monitor the environment of each Apollo landing site for a period of at least a year after the astronauts had departed [18]. Within a set of scientific instruments, two research groups conducted scientific experiment with radiometric transmitters of the Apollo landers.

2.1. ALSEP Double-Differential VLBI Program. MIT (Massachusetts Institute of Technology) research group observed ALSEP S-band radio transmitters by VLBI to improve determination of the positions of the ALSEPs and the parameters governing the motion of the Moon about its center of mass [19]. In the ALSEP Double-Differential VLBI program, a new device, DDR (Differential Doppler Receiver), was installed in six stations of NASA STDN (Spaceflight Tracking and Data Network) to support the project [20].

Tracking stations observed at least two of the five ALSEPs in each scan (Figure 1). Double differential observable is sensitive to the relative position of the two ALSEP transmitters, while is insensitive to other error sources, such as earth troposphere's effect on radio signal [21]. The program was formally conducted from March, 1973, and the first scientific result was based on observations conducted in about 130 days evenly distributed during the 16-month period. Based on ALSEP Double-Differential VLBI program, the uncertainties of the relative coordinates of ALSEP transmitter are 30m in the radial direction and 10m in the transverse plane, and values of lunar libration parameters have smaller uncertainty than the solution with only LLR data [22].

2.2. ALSEP-Quasar VLBI Program. The program ALSEP-Quasar VLBI was carried out by JPL (Jet Propulsion Laboratory) to accurately tie the lunar orbit to the new inertial quasar reference frame [23]. The program employed a "4-antenna" technique [24], a large antenna at each end of baseline observed the reference quasar, while smaller antenna which was attached to the large dish observed ALSEP (Figure 2). The advantage of 4-antenna technique is that the differential interferometric phase of each source without ambiguity for the length of the experiment is obtained; then, the differential phase could be used to derive angular separation between the reference quasar and the ALSEP transmitters on lunar surface. The precision is comparable to LLR, but is more sensitive in right ascension and declination instead of range [25].

Slade [26, 27] conducted covariance analysis for combining LLR data and 19 $\triangle$VLBI experiments over 37 months; the 19 $\triangle$VLBI experiments constrained the parameters twice as much as the 1600 laser range determinations over the same time span. However, the ALSEP were terminated since September 30th, 1977 [28]; then, no further reports about LRM with ALSEP were published to public.

3. OCEL Project

3.1. China Chang'E-3. China Chang'E-3 (Figure 3) soft landing on lunar surface is a key stone in CLEP (China Lunar Exploration Program), which stands for perfect finish of the phase II of CLEP [14, 29]. The X-band transmitter deployed on the lander opened up a new window for observing lunar surface with radiometric measurement from the earth.

Compared with LRM in Apollo era, precision of LLR has increased from orders of decimeters to less than 2 cm [3, 30]. Errors in the coordinates of the lunar beacons of ALSEPs 14 and 15 on the other hand are closer to 1m, and ALSEPs 12, 16, and 17 may have errors as large as 30m [31]. Moreover, during the past few years, lunar ephemeris has been improved by nearly three orders, and a several-orders-of-magnitude improvement of the variations in the Moon's rotation has been made [32]. It seems a big challenge to contemporary LRM for benefiting the Moon scientific research.

Nevertheless, the Chang'E-3 lander as an ideal radiometric beacon on lunar surface is a chance many lunar scientific researchers always pursue for. If the lander tracked accurately from the earth, landed spacecraft can be positioned with enough accuracy and would be useful for lunar geodesy [33]. Initially, observing X-band Chang'E-3 lander transmitter with VLBI could tie the lunar orbit to ICRF accurately [34]. An interesting fact about ALSEP is that, the original proposal, though not adopted, about applying VLBI to study the Moon by MIT is to deploy an X-band wideband (50MHz) noise source as the beacon, and the scientific objectives include determining the motion of the moon's center of mass against extragalactic radio sources [35]. Furthermore, the lunar librations are currently mainly calculated with LLR data, e.g., LLR data from 1970 to 2007 were used for the computation of the JPL DE421 and librations after 2007 are obtained by extrapolations [36]. As VLBI is more sensitive to the transverse plane, it could benefit correction to the three Euler angles which describe the lunar librations in principle, especially the angle between the direction of the Moon center to the Equinox and the intersection line of the Moon equator and the Earth equator [37, 38]. Additionally, with more accurate observable and enough tracking arc through experiment schedule, LRM data could be combined with LLR data in many aspects on earth and lunar science, including lunar ephemeris, lunar physics, and the Moon's interior [39].

3.2. Observing Chang'E-3 Lander with IVS Stations. The concept of OCEL (Observing the Chang'E-3 Lander with VLBI) was firstly introduced in the 8th IVS (International VLBI Service of Geodesy and Astrometry) General Meeting in 2014. Following observing proposal which was jointly

Figure 1: ALSEP Double-Differential VLBI program by MIT.

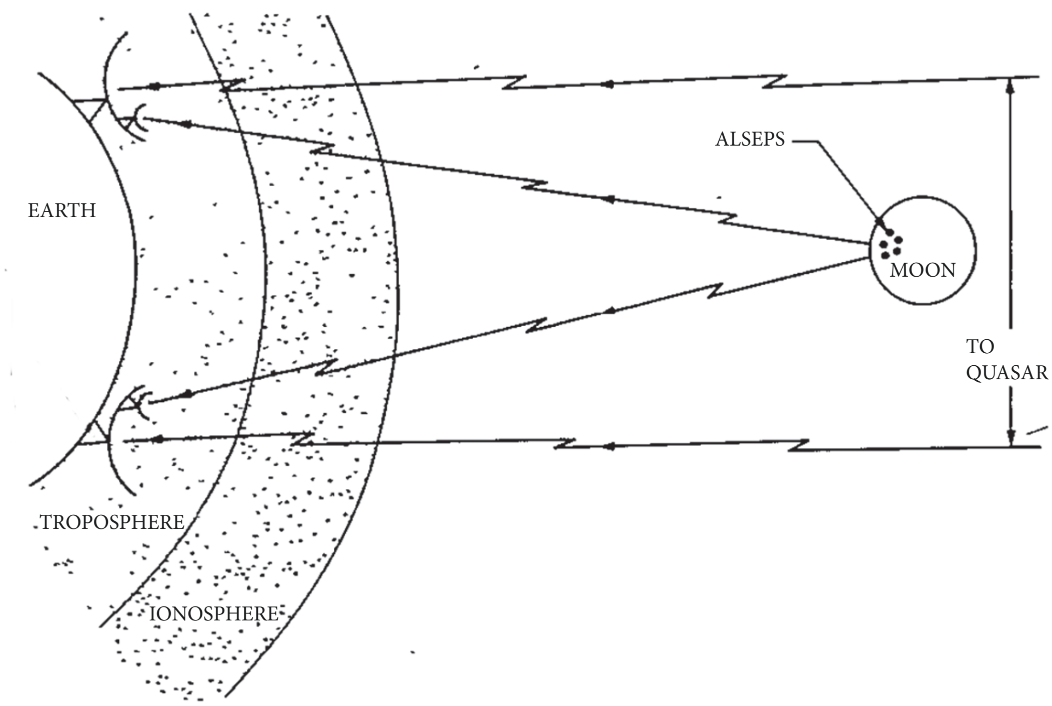

Figure 2: ALSEP-Quasar VLBI program by JPL [1].

drafted by BACC (Beijing Aerospace Control Center) and IVS Bonn Correlator Center to the OPC (Observing Program Committee) of IVS, OCEL was conducted by a global IVS R&D network (involving networks with 7 to 12 worldwide distributed IVS stations) (Figure 4) augmented with two China Deep Space Stations since 2014. The three LRM projects in history are compared in Table 1.

In the first 3-years observation (called phase I) of OCEL, Sweden Onsala Observatory is responsible for the schedule file where △DOR [40] mode is adopted, and the antennas track the lander and compact extragalactic reference quasar alternatively. In order to minimize the effect on other regular geodetic observation, OCEL observation is scheduled within IVS R&D session. The general scheduling strategy adopts alternating observing blocks of primarily 30 minutes length, where the observations are scheduled either geodetic observation or OCEL of each half an hour [41]. As strategies of frequency set-up, we schedule reference quasar and system attenuation changed across different sessions to find optimal OCEL observing system characteristic. The first phase of

Table 1: Comparison of different LRM.

	Agency	Tracking stations	Target	Frequency Band	Observable	Period & Span
ALSEP Double-Differential VLBI	MIT	STDN (Spacecraft Tracking and Data Network) 6 stations	ALSEP 12/14/15/16/17	S	phase (delay)	Mar 1973~Jul 1974 more than 130 days
ALSEP-Quasar VLBI	JPL	DSN (Deep Space Network) 3 stations Plus 'Apollo' station of STDN	ALSEP 12/14/15/16/17	S	Phase (delay)	Sep 1974~Sep 1977 19 △VLBI
OCEL (phase I)	IVS & BACC	subsets of the IVS observing network totally 15 stations participate	Chang'E-3 Lander	X	group delay	Jun 2014~Dec 2016 12 sessions

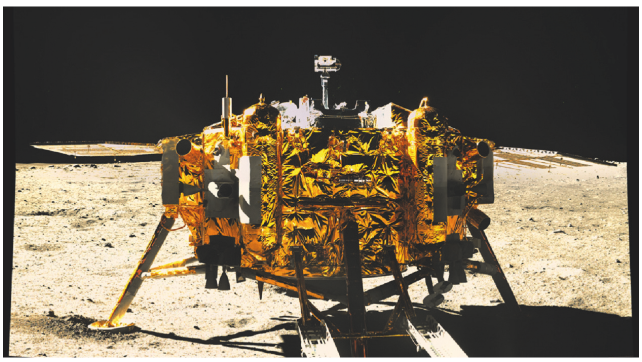

Figure 3: Picture of Chang'E-3 lander by Yutu Rover.

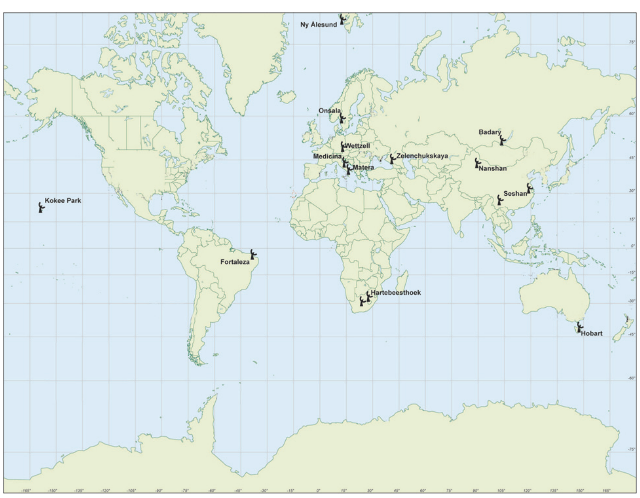

Figure 4: Distribution of IVS stations participating in OCEL.

OCEL finished at the end of 2016 and totally 12 observing sessions has been conducted successfully (Table 2). Taking session rd1601 (OCEL09) as an example, Figure 5 shows the quasar used for calibration and sky plot of station Onsala for the schedule file.

4. Preliminary Results and Discussion

4.1. Processing Strategy. BSCS (BACC Software Correlator System) is adopted for data correlation and fringe fitting in BACC [42]. IVS Bonn Correlator Center deploys DiFX [43] and CALC11 for computing apriority model of near field target. The standard fringe fitting program used in connection with geodetic correlators is the HOPS (Haystack Observatory Processing Software) component "fourfit" [44], and a refreshed version "fourfit-DOR" is developed which extends the fringe fitting algorithm of "fourfit" to allow for processing of DiFX correlation output of DOR tones [45].

△DOR theorem and application are widely discussed [15, 46]; in OCEL, geodetic observations with different systematic frequency altered each half an hour, and the change in channel parameter caused delay offsets. So each block with continuous scans (usually half an hour) within a session is calibrated separately, and meteorological data recorded in tracking stations is used to improve the accuracy of apriority atmospheric delay. After calibration with reference quasar, observable of the lander is used for analysis.

4.2. Position Determination. Position determination of the radiometric beacon is the foundation of scientific analysis. The theoretical basis of estimating parameters with the observables by weighted least-square fitting is widely discussed and adopted [47], and the state matrix of partial derivatives with elements of VLBI is analyzed in detail [11, 48].

As VLBI observable is less sensitive to radial direction (similar to X-axis), two strategies are induced to make the results more stable and reliable. One approximate method is that, as the area of the landing site with reliable height information is deemed as flat, then a self-constrain strategy is induced [36].

$$\sqrt{X^2 + Y^2 + Z^2} = \sqrt{{X_0}^2 + {Y_0}^2 + {Z_0}^2} \qquad (1)$$

where X, Y, Z are the 3-dimensional coordinates of the lander and X_0, Y_0, Z_0 are the default coordinate values from LRO (Lunar Reconnaissance Orbiter). The other more reliable method is that UXB (Unified X-Band) observables are combined. In our analysis, one-hour arc of two-way ranging observable from KASHI Deep Space station is combined with observables in OCEL to make position determination. The reason is that ranging tracking is conducted continuously just before Chang'E-3 soft landing, during EDL (Entry Decent Landing) and the first one hour after landing on lunar surface, so the ranging systematic error is stable during the whole tracking arcs. The accuracy of orbit determination for

Table 2: IVS stations participating in OCEL (working mode 1 stands for coherent transmission, 2 stands for one-way; Bd-Badary, Ft-Fortaleza, Hh-Hartebeesthoek, Ho-Hobart26, Ht-Hart15, Kk-Kokee, Km-Kunming, Ma-Matera, Mc-Medicina, Ny-NyAlesund, On-Onsala, Sh-Seshan25, Ur-Urumqi, Wz-Wettzell, Zc-Zelenchukskaya).

Sessions	01	02	03	04	05	06	07	08	09	10	11	12
	Bd	Bd	Bd	-	Bd	Bd	Bd	Bd	Bd	Bd	Bd	Bd
	-	-	-	-	Ft	Ft	-	Ft	Ft	Ft	Ft	Ft
	Hh	Hh	-	-	Hh	Hh	Hh	-	Hh	Hh	Hh	Hh
	Ho	-	Ho	Ho	Ho	Ho	Ho	Ho	Ho	Ho	Ho	Ho
	-	-	Ht	Ht	-	-	-	Ht	-	-	-	-
	-	-	-	Kk	Kk	Kk	Kk	Kk	Kk	-	Kk	Kk
	-	-	-	-	-	-	-	-	-	-	Km	-
Tracking stations	-	Ma	Ma	Ma	Ma	Ma	Ma	Ma	Ma	-	-	Ma
	-	-	-	-	-	-	-	-	-	Mc	Mc	-
	Ny	Ny	Ny	Ny	Ny	Ny	Ny	Ny	Ny	Ny	Ny	Ny
	On	-	-	-	On	On	On	On	On	-	On	On
	Sh	Sh	Sh	-	Sh	Sh	-	-	-	Sh	-	-
	-	Ur	Ur	Ur	-	-	-	-	-	Ur	Ur	Ur
	Wz	Wz	Wz	Wz	Wz	Wz	Wz	Wz	Wz	Wz	Wz	Wz
	Zc	Zc	Zc	-	Zc	Zc	Zc	Zc	Zc	Zc	Zc	Zc
Working mode	1	1	1	1	2	2	2	2	2	2	2	2

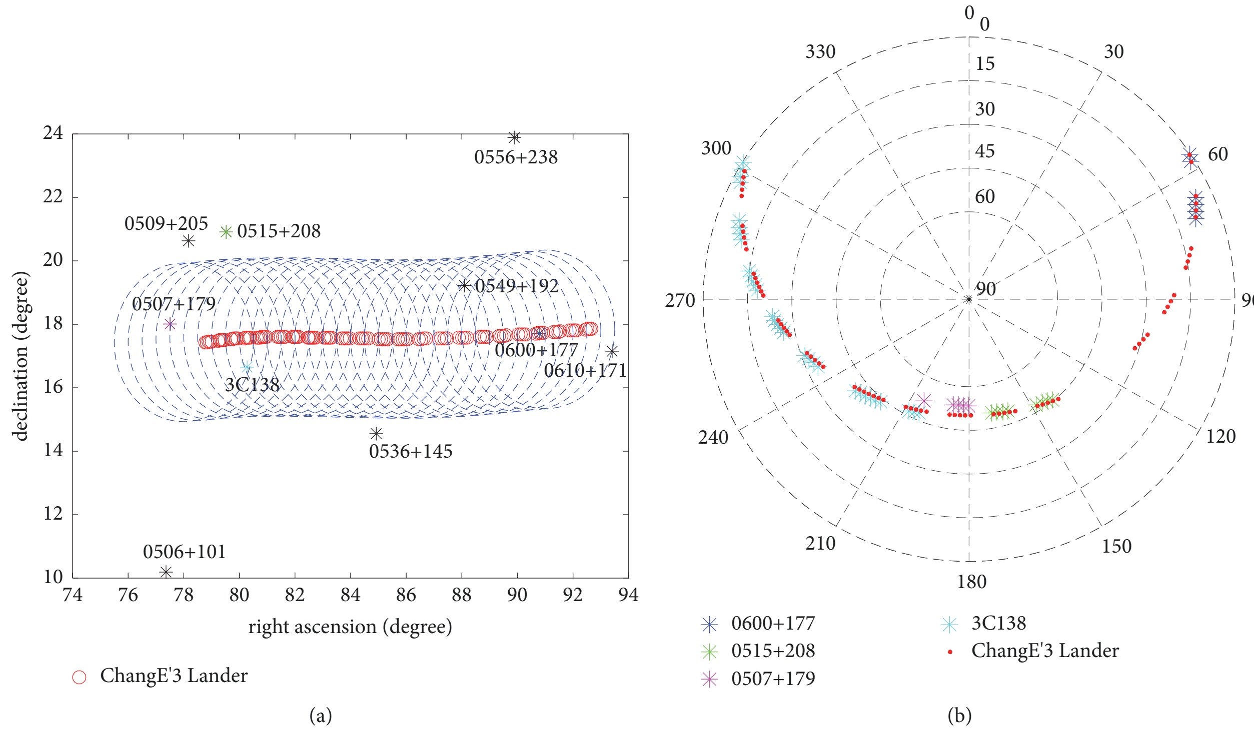

Figure 5: ChangE'3 lander position and sky plot of Onsala within session rd1601.

Table 3: Correction of coordinates.

Observable type	△X(m)	△Y(m)	△Z(m)
VLBI	-501.954	-44.021	-32.299
VLBI+self-constrain	15.448	-3.231	-16.115
VLBI+Ranging	13.837	-2.483	-4.007

Table 4: Coordinates comparison.

	Latitude(°)	Longitude(°)	H(m)
LRO	44.1214	340.4884	-2640
[11]	44.1188	340.4874	--
[12]	44.1219	340.4887	--
[13]	44.1213	340.4885	--
[14]	44.1206	340.4876	-2632
[15]	44.1189	340.4907	-2637.6
this paper	44.1210	340.4882	-2632.8

circular orbit is better than 20 meters, and the accuracy in radial is in the order of meter (better than 5 meters) [48], which could restrain ranging accuracy better than 5 meters with systematic error removed. Besides, positioning result of GSFC (Goddard Space Flight Center) by LRO is deemed as a default value [12]. Table 3 shows the correction of the lander coordinates in Principle Axis with different resolution strategy.

The result is compared with other published results, as listed in Table 4. Consistence of positioning results by remote image matching is affected by the basic reference image adopted, and it could be identified that literature [13] is a little different from LRO/[49]/[50], as the reference image is acquired by Chang'E-2.

Figure 6 shows the positioning results with maximum ranging systematic error (5m) existed. The height varies about 3.46m caused by ranging systematic error, while tangent plane on lunar surface is about 3.04m (Figure 6). The difference of positioning results from LRO is about 7.2 meters in height and about 14 meters in plane on lunar surface.

4.3. Data Process Analysis. Accuracy analysis of △DOR is shown in literatures [51]. In phase I of OCEL, there is the first observation for most IVS radio telescopes which are set up almost exclusively for observations of faint signals of natural radio sources, so adjustments of channel frequency and bandwidth parameter setting up are sometimes being carried on during the whole OCEL phase I. Based on our analysis, main sources which deteriorate the accuracy may be grouped into three general categories in OCEL.

The contrast in signal strength between reference quasar and the lunar lander might be challenging for the receiving system. Though the higher power signal of lander does not saturate the VLBI-systems which adjust attenuation with automatic gain control or with an experienced value, phase offset may exist in an alternating scan mode for some stations (Figure 7).

The phase offset will deteriorate group delay accuracy if not compensated properly, so stations without PCAL (phase calibration instrument) and sessions within which PCAL is not active are not reliable for observable analysis.

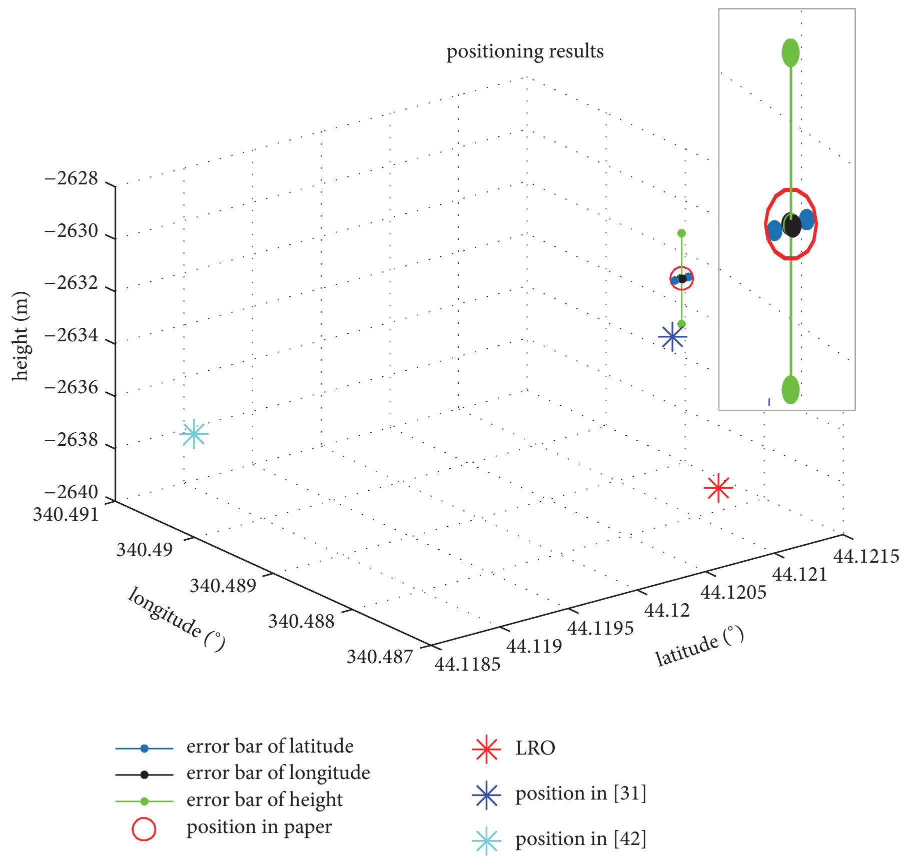

Figure 6: Comparison of positioning results with respect to ranging systematic error.

In OCEL, geodetic observations were carried out within each session with half-an-hour interval. Geodetic observation of the first ten sessions was carried out with a frequency set-up used in routine IVS-sessions, which was different from lunar observation. The change in channel frequency set-up caused delay offsets in some baselines (Figure 8).

The systematic offset limits the length of tracking arc of reference quasar used for parameter estimation, such as clock offset, clock drift, and residual tropospheric delay, including dry and wet component. In the case of reference quasar with lower SNR within half-an-hour short arc, the reliability of parameters estimated from reference quasar becomes lower, which will deteriorate the accuracy of the lander observable at last.

Besides, the SNR of reference quasar could also affect the accuracy of lander observable through residual systematic delay calibration. In OCEL, spanned bandwidth is less than 40MHz, compared with 720MHz in X-band of IVS general sessions; a conservative angular sensitivity would be worse by nearly 20 times. Higher SNR will benefit accuracy of reference quasar and also will improve lunar lander observables through △DOR. Statistics show that the random error of observable is about 1ns in OCEL. Figure 9 shows X-band SNR of reference quasar of all baselines in OCEL09, calculated using the following equation:

$$\delta_{\tau} = \frac{1}{2\pi \cdot \sqrt{(1/N)\sum_{i=1}^{N}\left(f_i - f_{ave}\right)^2} \cdot SNR} \qquad (2)$$

where f_i is the frequency of channel used for bandwidth synthesis and f_{ave} is the average frequency.

Based on the experiment accuracy analysis, in order to enhance the contribution to Earth-Moon scientific topics where position accuracy better than 1 meter is needed [39], both the processing strategy and observing mode would be optimized. One of a prospective program is being researched. In this case, sites with two geodetic antennas or more will participate in the observation, such as Wettzell, Hartrao, and Hobart, and one antenna observes the lander while the other antenna observes a small angular-separated quasar with stronger flux. Firstly, the phase-delay observable is expected, which would improve the delay observable by two orders. Secondly, phase fluctuation caused by frequency standard could be eliminated if the two antennas share common maser. Thirdly, while the lander and the reference quasar with smaller separated angle are observed at the same time, time-varied error could be calibrated as much as possible. Last but not least, longer arc will be adopted in schedule which will benefit the systematic parameter calibration.

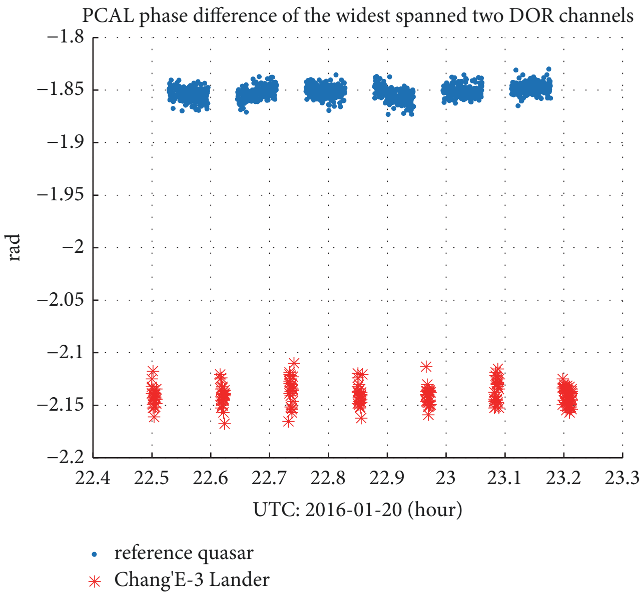

Figure 7: Phase offset between the altering scans of station NYALES20 in OCEL09. (In this case, the integration time is 1s, phase offset between reference quasar and lunar lander is as large as 16.5°, which equals 1.2ns offset in the group delay observable.)

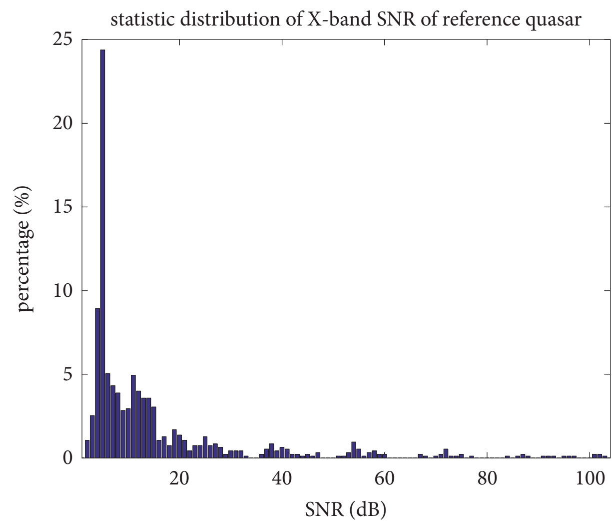

Figure 9: X-band SNR of reference quasar of all baselines in OCEL09. (In this case, 4 channels corresponding to DOR tones channel are used for bandwidth synthesis. Though designed SNR value is 35dB, SNR from 7dB to 15dB takes up nearly 40%, and most of lower SNR observables come from baselines combined with station FORTLEZA.)

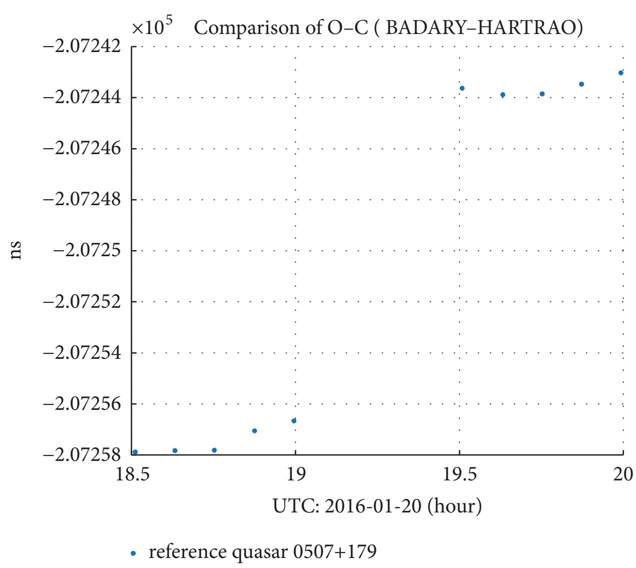

Figure 8: Delay offset caused by system channel setting up variation. (In this case, from 19:00~19:30 geodetic observation with different frequency set-up is conducted, when system parameters change back to OCEL observation, delay offset could be identified, most of O-C belongs to station clock.)

5. Conclusions

Observing lunar surface with radiometric tracking is always a pursuit in the field of Earth-Moon scientific since Apollo era. The successful Chang'E-3 soft landing makes it come true after nearly 50 years. The first phase of OCEL has been successfully conducted jointly by IVS and BACC. Performance and ability of IVS geodetic tracking stations are evaluated, correlation and data reduction algorithm are also refreshed for artificial satellite signals, and preliminary positioning result which could be consistent in the magnitude of 15 meters is analyzed and discussed. With optimized observing mode and processing strategy, further OCEL sessions will be conducted to make use of this target-of-opportunity as long as Chang'E-3 is working, which is expected to make progress on earth and lunar science.

Data Availability

Raw OCEL data could be available under the approval of the project organizer.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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