Initial Estimations of the Lunar Lander Position by OCEL Observations

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Abstract The successful landing of the Chang'E-3 lunar lander, opened up the window for observing the moon with VLBI again after more than 40 years. *Observing Chang'E-3 with VLBI* (OCEL) is conducted as an IVS Research and Development project with 12 sessions observed and being processed. Presently, the position of the lunar lander on the Moon is in the focus to be determined. In this study, two OCEL observing sessions of the lunar lander have been processed preliminarily. Based on precise information of the moon's motion provided by ephemeris, the position of the lunar lander in a Moon-fixed system is determined. Since VLBI is much less sensitive to the radial direction, a constraint for the lunar distance is applied. The results show that with this constraint based on a priori information, a position of the lander on the Moon was determined which about ten meters off the position from Lunar Reconnaissance Orbiter results. Accuracy analyses are carried out with positioning results from other approaches. Analysis shows that the accuracy of the positioning with the preliminary observations is about 30 meters.

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1 Introduction

As the only natural satellite of the Earth, holding the information of the Earth-Moon system dynamics and motions, the Moon has always been a prime object of interest for space sciences. For the first time in 1969, the Apollo program laid the groundwork to obtain direct geodetic measurements of the Moon. With the Apollo program, the Apollo Lunar Surface Experiments Package (ALSEP) (King, 1976) was carried to the Moon, which comprised a set of scientific instruments placed at the landing sites. With these instruments, VLBI observations were possible for a few years while Lunar Laser Ranging observations can be carried out today and beyond. These data have made significant contributions in many scientific fields.

The determination of coordinates of any lunar lander have always been of great importance for lunar investigations. Earlier studies have been carried out to estimate the coordinates of beacons on the lunar surface with VLBI observations. For instance, based on ALSEP Differential VLBI Observations, the uncertainties in the relative coordinates of ALSEP transmitter were reported by an MIT (Massachusetts Institute of Technology) research group to be 30 meters in the radial and 10 meters in the transverse components (King, 1976). Cao et al. (2016) used VLBI and unified X-band (UXB) observations of several hours arc from 4 stations to estimate the coordinates of the Chang'E-3 lunar lander and obtained coordinates in the Mean Earth (ME) frame which are different by 0.0025°, 0.0023° and 3 meters in latitude, longitude and altitude, respectively, from coordinates by Lunar Reconnaissance Orbiter (LRO) determinations (Mazarico et al., 2012).

In December 2013, the deployment of the Chang'E-3 lunar lander on the Moon and its capability to transmit X-band signals opened up the window for new lunar VLBI observations from the Earth again after more than 40 years (Zheng et al., 2004). The concept of *Observing Chang'E-3 Lander with VLBI* was firstly induced by Tang et al. (2014). Following observing proposals to the Observing Program Committee (OPC) of the International VLBI Service for Geodesy and Astrometry (IVS) (Nothnagel et al., 2017), four 24 hour sessions each were scheduled and conducted with subsets of the IVS observing network and 2 China Deep Space Network stations in 2014, 2015, and 2016 (Haas et al., 2017). Two of these sessions (OCEL-1 and OCEL-9) are available for geodetic analysis at the moment producing initial results for the lunar lander position.

2 Theory for the lunar lander positioning

Since the lunar lander is fixed to the surface of the Moon, the coordinates are approximately constant in the Moon-fixed coordinate frames without considering the tidal effects. Then its equations of motion only involves the transformation between the Moon-fixed coordinate frame(s) and the inertial frame. The locations of features on the lunar crust are usually described by coordinates expressed in the mean-Earth (ME) frame, in which the X axis is defined by the body-fixed axis that points toward the mean Earth direction and the Z axis points toward the mean rotation axis direction (Folkner et al., 2008, 2014). The ME frame is in contrast to the principal axis (PA) frame which considers the gravity field of the Moon. Coordinates in the ME frame (vector M) can be rotated into the PA frame (vector P) using

$$P = R_z(C) * R_y(B) * R_x(A) * M \quad . \tag{1}$$

Conversely, coordinates in the PA frame can be rotated into the ME frame with

$$M = R_x(-A) * R_y(-B) * R_z(-C) * P \quad , \tag{2}$$

where the R_x, R_y and R_z are the standard rotation matrices for right-handed rotations around the X, Y and Z axes, respectively, and A, B and C are the angles given in Table 1.

Because the procedure for calculating the constant rotation angles changed, there are different values of the constant angles for each JPL ephemeris listed in Table 1. By comparing the angles for DE403 (same as DE405) and DE421, the differences are up to about −0.15", 0.51" and −4.02",and the displacements in the PA frame from DE421 are 5.1, −1.0 and 2.6 meters, respectively. The constant rotation angles for DE421 and DE430 are below 1". Note that the angles for the transformation are computed only to first order. The second-order contribution is a rotation about 0.03"(0.25 meters on the lunar surface), and the error in the first-order expression is estimated to be half of that, i.e., 0.015"(0.11 meters). As we describe in Table 1, the differences of the three angles between DE430 and DE421 are 0.015", 0.020" and 0.347" (0.11, 0.16 and 2.9 meters), respectively.

Table 1: The angles for transformation from the ME frame to the PA frame corresponding to the JPL ephemeris.

	DE403/DE405	DE421	DE430
Angle A (arcsecond)	0.1462	0.30	0.285
Angle B (arcsecond)	79.0768	78.56	78.580
Angle C (arcseond)	63.8986	67.92	67.573
Differences in PA (meters)	5.1/−1.0/2.6	0/0/0	0.6/−0.1/0.1

The difference in the coordinates of a point on the surface of the Moon between the ME frame and the PA frame is approximately 860 meters. As recommended by the International Astronomical Union (IAU) for high precision working, e.g., spacecraft operations involving the orientation of the Moon, a lunar ephemeris should be used to obtain the libration angles for the Moon, which define the rotation from the PA frame to the inertial ICRF frame (Archinal et al., 2010). There are no equations of the motions for Euler angles referenced to the ME frame. The Euler angles provided by the JPL ephemeris are numerically integrated and inherently more accurate than the knowledge on the mean axes. The constant three-angle rotation from the PA frame to the ME frame is known less accurately than the integrated Euler angles, however this is enough for meter or lower level accuracy. Because of this, we use the coordinates in the PA frame for estimating the position of the lunar lander. It should be mentioned that the coordinates of the lunar lander obtained from LRO photographing data, which we use as a priori values, are in the ME frame. For comparison, our position estimates in the PA frame are thus converted to the ME frame a posteriori.

In this preliminary data analysis, we used only the lunar observations and those quasar observations designed for delay calibration purposes (Haas et al., 2017). With the calibration observations clock offsets were determined for segments of about two hours each in a very rudimentary least squares adjustment. These, together with corrections for the hydrostatic components of refraction, were used to roughly calibrate the observations. Of course, this is a very rough procedure but it is sufficient for a first quick glance at the observables (see Sec. refsec:results). Telescope coordinates from the ITRF2014 solution (Altamimi et al., 2016) were transformed with the usual correction models. Then a standard least squares adjustment is performed which estimates only the lunar lander position components.

3 Observation Data

Since currently no complete OCEL session is processed, a number of preliminarily processed observations from two sessions are used here for the initial estimation.

The raw data of OCEL sessions are correlated with the correlator software DiFX-2.4 (Deller et al., 2007). The fringe-fitting of the quasar observations is processed with HOPS-3.12(fourfit), and the lunar lander observations are fringe-fitted in a special DOR tone signal processing method (Kikuchi et al., 2004).

Table 2: The sessions and baselines of the observations used for the estimation.

Sessions	Baselines
OCEL-01 (RD1405)	BD-SH, HT-ZC, SH-ZC
	BD-KK, BD-WZ
OCEL-09 (RD1601)	BD-ZC, BD-HO, WZ-ZC
	BD-NY, NY-ZC, KK-NY

The OCEL-01 session was conducted in July, 2014, and the OCEL-09 in January, 2016. Five baselines from OCEL-01 and six baselines from OCEL-09 were used in the lunar lander positioning, and the number of the observations used were 119 and 89 respectively as shown in Table 2. The sessions provided observations of the lunar lander and of some nearby quasars (Haas et al., 2017). In addition, also a large number of standard VLBI observations had been gathered in these sessions but these are not used in this initial data analysis.

4 Results

According to the theory described above, the position of the lunar lander is estimated using about 200 successful VLBI observations. Taking the coordinates of the lunar lander from LRO as the a priori values, the corrections w.r.t. these coordinates from LRO in the PA frame are estimated (Table. 3). The adjustments to the Y and Z components are around 40 and 30 meters, but for the X component it is almost 500 meters. The reason is that the observations are hardly sensitive to this direction.

Table 3: The corrections w.r.t the coordinates of the lunar lander from LRO in the PA frame.

	X	Y	Z
Corrections in PA (m)	−491.5	−43.1	−30.4
STD (m)	34.9	3.8	2.9

The weighted RMS (WRMS) residual delay is only 30.8 ns which corresponds to about 9 m. This of course is still very rough but matches the position uncertainties.

For the lack of sensitivity of VLBI to the radial component, which corresponds to the X-axis of the Moon, a constraint needs to be introduced from a priori information. In this case, the lunar lander is fixed on the surface of the Moon with the distance between the center of the Moon and the lunar lander being introduced as a constant. This constraint can be formulated as

$$\sqrt{X^2+Y^2+Z^2} = \sqrt{X_0^2+Y_0^2+Z_0^2} = const., \tag{3}$$

where X, Y and Z are the coordinates to be estimated, and X_0,Y_0 and Z_0 are the coordinates based on the a priori coordinates from LRO. With this constraint applied, the WRMS residual delay increases considerably to 44.9 ns but the X component reduces to a reasonable number (Table. 4). It should be taken into account that since the constraint is based on the a priori values, the accuracy of the a priori value heavily affects the positioning results. In some sense this is reflected in the increased formal error of this and the Z parameter.

Table 4: The corrections with constraint w.r.t. the coordinates of the lunar lander from LRO in PA frame.

	X	Y	Z
Corrections in PA (m)	10.0	−4.3	−10.9
STD (m)	25.4	2.5	11.3

The photographic positioning results of the lunar lander from LRO are given in the ME frame, based on the JPL ephemeris DE421 and a radius of the Moon 1737.4 km. Table 5 shows the polar coordinates of the lander from the initial VLBI estimation, from the VLBI estimation with constraint and from LRO, all in the ME frame. The differences are 0.0096° in latitude, −0.0021° in longitude and −343 m in altitude between the coordinates from VLBI estimation and LRO. With the constraint, the differences are improved to −0.0005°, −0.0002° and 0 meters in latitude, longitude and altitude respectively.

At this point, we should also discuss the accuracy of the reference position of the lander stemming from LRO

Table 5: The geodetic coordinates of the lunar lander from the initial VLBI estimation, from the VLBI estimation with constraint and from LRO, all in the ME frame.

	VLBI (Tab. 3)	VLBI (Tab. 4) with constraint	LRO
Latitude (°)	44.1310	44.1209	44.1214
Longitude (°)	−19.5137	−19.5118	−19.5116
Altitude (m)	−2983	−2640	−2640

photography. The camera on LRO is reported to have a resolution of up to 0.5 meters (Mazarico et al., 2012; Liu et al., 2015). After some modifications to the control of the lunar orbiter laser altimeter (LOLA) during the mission, the accuracy of the photographic positioning with a single photograph of LRO is estimated to be about 20 meters. This accuracy can be increased by stacking a number of photographs (Mazarico et al., 2012; Liu et al., 2015). Comparing our results with those from LRO based on different numbers of photographs shows differences in the range of 0.0003° to 0.0005° corresponding to about 9 to 15 m on the lunar surface which are just within the accuracy of LRO positioning 20 meters (Table. 6).

From the initial spacecraft navigation observations (Cao et al., 2016; Li et al., 2014) more results are available for comparison. Compared to positioning results from VLBI and Unified X Band (UXB) measurements for range and range rate observations in the initial mission period (2014), our results differ by about 50 meters and 80 meters, respectively (Table. 6). However, these reference results are based on a much smaller number of observations. So, presuming that the accuracy of the LRO photographic positioning is just 20 meters, our results agree quite well with these references even though we have just applied a very rough analysis scheme.

Table 6: Current positioning results with different approaches and data. VLBI+UXB from Cao et al. (2016) and Li et al. (2014).

Approaches	Latitude (°)	Longitude (°)
VLBI, this paper	44.1209	−19.5118
LRO (1 photograph)	44.1214	−19.5116
LRO (5 photographs)	44.1213	−19.5115
LRO (14 photographs)	44.1219	−19.5113
Mission VLBI+UXB (initial)	44.1189	−19.5093
Mission VLBI+UXB	44.1206	−19.5124

5 Conclusions

This paper describes a very preliminary determination of the position of the Chang'E-3 lunar lander. With about 200 VLBI group delay observations the position is estimated in a very rough least squares solution. Considering that VLBI has hardly any sensitivity in the radial direction, a constraint based on the a priori information from LRO is applied. With this constraint, the position difference in radial direction relative to LRO photographic positioning reduces from 500 m to about 10 meters. Also the differences in the transverse directions are estimated to have the same magnitude of about 10 meters. These results are very motivating for refined analyses both in fringe fitting and VLBI modelling with more data of more observing sessions.

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