Relative position determination between lunar lander and rover using same beam VLBI technique

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1. Introduction:

The first Chinese lunar explorer Chang'E (CE)-1 was launched on October 24, 2007, and one of the follow-on missions, CE-2 was launched on October 1, 2010. According to the planned schedule, Chinese unmanned lunar exploration plan is divided into three stages: orbiting, landing and returning stages. In the orbiting stage, the CE-1 and CE-2 satellites orbit around the moon and gather data on the landing area. During the landing stage, the main task is to land and operate a rover on the lunar surface autonomous scientific exploration.

In China's 3rd lunar exploration project, Chang'E-3 mission, a lander and a rover will be placed on the lunar surface. The lander is not movable, and the rover will explore the Moon automatically. The rover will be in moving and standstill state interchangeably [1]. The precise positioning of the lander and the rover is very important in achieving the scientific goals of the Chang'E-3 mission. This paper focuses on the relative position determination between the lander and the rover (while at standstill) using the same beam Very Long Baseline Interferometry (VLBI) technique.

In the multi-frequency same beam VLBI observations, two explorers with small separation angles are observed simultaneously with the main beam of the receiving telescopes (Figure 1). Because the separation angle of the two explorers is small, the influences of the atmosphere, the ionosphere and the time delay in the instruments are almost canceled from the difference in the correlation phase, thus high accuracy differential VLBI delay can be achieved [1]. The relative position between the lander and the rover on the lunar surface can thus be determined precisely by using the differential VLBI delay.

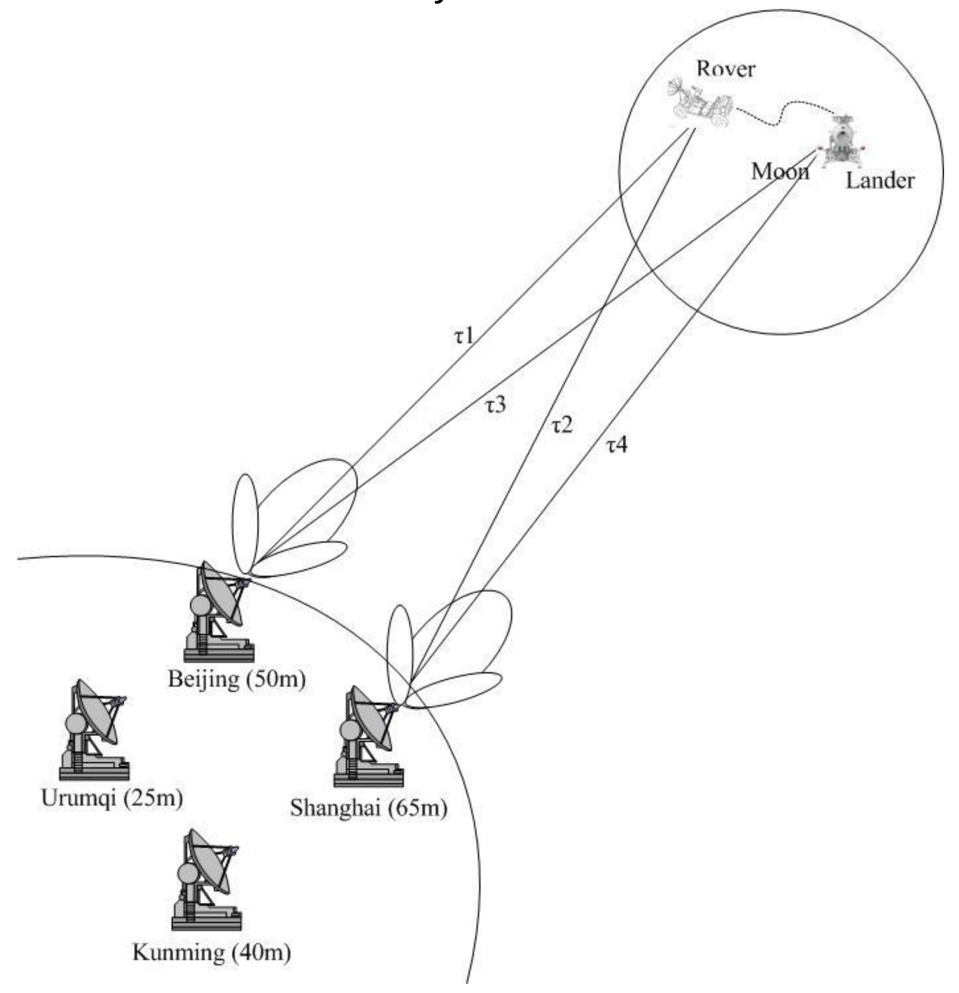

Figure 1: The same beam VLBI observations between a rover and a lander, and the four Chinese VLBI stations: Beijing (50 m),Kunming (40 m), Shanghai (65 m) and Urumqi (25 m).

2. Methodology

A kinematic statistical method is proposed [2], which uses measurements of a continuous arc, combining with the motion of the Moon, to get the position of the lander/rover on the lunar surface with high accuracy. This statistical method uses all observations over a observational time period, not a single point, to determine the position of a lunar lander/rover, so the position accuracy is much higher than that of single point positioning.

There are similarities as well as significant differences between the kinematic statistical positioning for the lander/rover and the traditional Orbit Determination (OD) for a satellite. Both use statistical method to get high accuracy. For the satellite, its motion around the center body is described with the forces exerting on the satellite, and the observations at various epochs are integrated via the state transfer matrix (STM) and processed simultaneously [3]. Because the lander/rover is not moving on the lunar surface, it is easy to establish the model of motion in inertial system, according to the motion of the Moon. The model accuracy is only depended on the accuracy of lunar orbit and rotation, which can be obtained using planet planetary ephemeris (such as JPL DE/LE403, 421) [4].

3. Error analysis

The main error sources affecting the positioning accuracy are measurement errors, which including the noise and the systematic bias, as well as errors of lunar orbit and rotation involved in the lunar ephemeris.

Nowadays the primary means to investigate lunar orbit and liberation is still the lunar laser Ranging (LLR). The LLR observations are distances between the ground station and the reflector located on the lunar surface. From 1969 till now, the accuracy of LLR observations raised from 30cm at the very beginning to 10~15 cm in the 1980s , 3~5 cm in the 1990s, and ~2 cm level at present. The primary purpose of LLR is to demonstrate the equivalence principle of Einstein's theory of relativity, however, with the development, LLR is used for determine the Earth Orientation Parameters (EOP), station coordinates, precession, nutation, parameters of lunar movements and liberation, coordinates of lunar surface reflectors and so on. One of the scientific contributions of the LLR is that it significantly improved accuracy of the lunar orbital motion, and contributed to the generation of high-precision lunar ephemeris.

DE403 was built in 1995, and the updated series DE418 and DE421 ephemeris are using more LLR observations. For example, DE421 was using nearly 30 years LLR observations from 1970 to 2007, and achieving higher accuracy. The lunar position differences between DE418 and DE421 can reflect the model errors from a certain extent. Moreover, the lunar position difference in 2010 is up to 5m between DE403 and other two ephemerides. However, it is about 0.5m between DE418 and DE421. Therefore, JPL recommends the DE421 ephemeris in the following lunar exploration program.

Based on the above analysis, the effect of errors in the Moon model to the position calculation should be small. Therefore, the main errors are from measurements, this paper focuses on analyzing the impact of measurement errors on position calculation.

4. Simulation and result

Simulation data are applied to analyze the relative positioning accuracy between the lander and the rover, using the software developed at Shanghai Astronomical Observatory (SHAO).

Assuming the lander is located at the center of Sinus Iridum (the future landing area for Chang'E-3, Figure 2). The 'true' parameters for simulation are:

The Lander: 44.1° N , 31.5° W, -3338.0 m (ULCN2005 model).
The Rover : 44.0° N, 31.4° W, -3333.0 m.
(The distance between the lander and the rover is about 3 km)
Observations: VLBI network of 4 antenna.
Noise level: 0.01 ns (SBI-delay, 1σ), data sampling interval is 5 seconds.

The simulated observations are used to calculate the relative position between the lander and the rover. In the calculation, we add an error of 1 km in horizontal position, and 100m in elevation to the true values as provided in previous paragraph, thus assuming the prior position to be:

The Lander: 44.13° N, 31.53° W, -3238.0 m.
The Rover : 44.13° N, 31.53° W, -3238.0 m.

Here we fix the position of the lander, and solve only the position of the rover and so at most 3 parameters are solved.

Table 1 gives the simulation result as well as the accuracy of the relative positioning. Different bias levels in same beam VLBI delay from zero to 1 ns are considered. Two strategies are adopted. Strategy 1 solves all 3 parameters in the rover position; Strategy 2 solves only 2 horizontal parameters, fixing the prior elevation parameter. All two strategies consider various arc lengths from single epoch to 30 minutes.

Table 1 shows:

(1) If arc length is short or there are not enough observations, the accuracy of strategy 2 will be better than the strategy 1. The elevation difference of the lander and rover should be small in Sinus Iridum for the flat terrain, so the strategy 2 will be useful in Chang'E-3 mission.

(2) With the bias increasing in SBI delay, the relative positioning error becomes larger. In the VLBI data processing, the bias will become smaller while arc length increases, so enough arc length is necessary to solve for same beam VLBI bias.

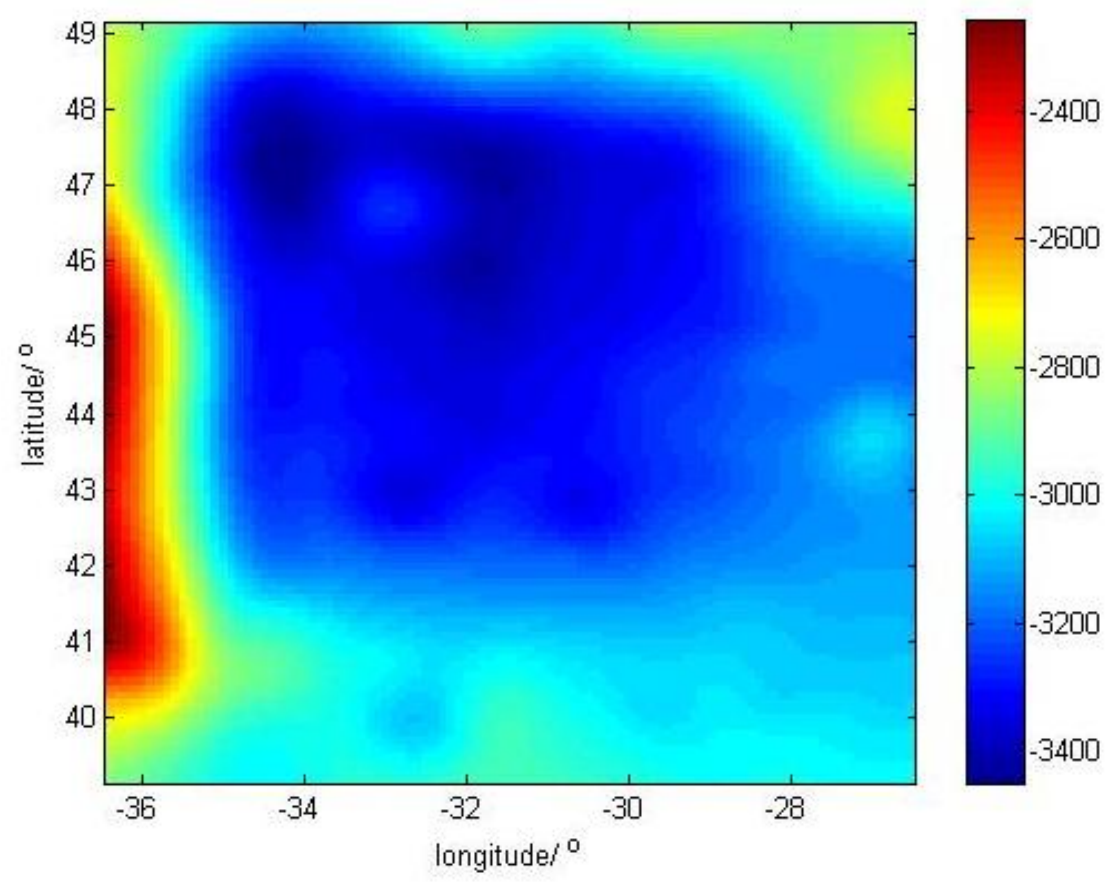

Figure 2: The elevation graph of Sinus Iridum area using ULCN2005 model

5. Summary

In this study, the relative position accuracy between the lunar lander and the rover in Chang'E-3 mission is analyzed. A kinematic statistical method is used in the simulation analysis using same beam VLBI observations with a noise level of 0.01 ns. The results show that with arc length of 5 minutes or longer, assuming the bias in same beam VLBI delay will be decreased to about 0.5 ns, the corresponding relative position accuracy between the lander and the rover can be better than 50 m.

Table 1. The relative positon accuracy summary (unit: meters)

Bias / Arc		0ns		0.2ns	0.5ns	1ns
		Strategy 1	Strategy 2	Strategy 2	Stragety 2	Stragety 2
Single epoch	lat.	222.80	4.44	-1.75	-10.58	-25.61
	lon.	226.88	0.09	-6.99	-17.93	-35.96
	el.	309.04	-5	-5	-5	-5
5 min.	lat.	12.48	2.87	-3.26	-12.02	-26.90
	lon.	9.43	0.20	-6.87	-17.78	-35.77
	el.	18.53	-5	-5	-5	-5
10 min.	lat.	13.17	2.82	-3.25	-11.91	-26.65
	lon.	16.14	0.23	-6.83	-17.73	-35.68
	el.	16.87	-5	-5	-5	-5
20 min.	lat.	7.51	2.82	-3.14	-11.63	-26.07
	lon.	10.47	0.24	-6.79	-17.65	- 35.54
	el.	9.03	-5	-5	-5	-5
30 min.	lat.	0.13	2.81	-3.02	-11.34	-25.49
	lon.	3.13	0.23	-6.78	-17.61	-35.45
	el.	1.15	-5	-5	-5	-5

References: [1] Liu Q. et al. (2010) Sci China, 53(3), 571–578. [2] Huang Y. et al. (2012) Chinese Science Bulletin, 57(35), 4545-4551. [3] Li P. et al. (2011) Sci China (in Chinese), 41(7), 889-895. [4] ftp://sd.jpl.nasa.gov/pub/eph/planets. [5] Archinal B.A. et al (2007). Lunar and Planetary Science, XXXVIII, 1904.