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Contribution of simulated space VLBI to the Chang'E-1 orbit determination and *EOPs* estimation

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ABSTRACT

Space very long baseline interferometry (SVLBI) is an extension of ground based VLBI to space, which has advantages, such as improving the precision and geometry structure of time delay observables with interconnecting multiple spatial coordinate systems directly. In this paper, a mathematical model of relativistic simulated SVLBI observables for estimating Chang'E-1 (CE-1) transfer orbit and Earth orientation Parameters (*EOPs*) is derived and discussed. A comparison of parameter estimation precision between ground ΔVLBI measurements and simulated SVLBI observables is carried out to verify the contribution of SVLBI. The optimal observation condition of CE-1 for SVLBI simulated observables is determined based on the analysis of parameter estimation results under CE-1 current observation condition. By using simulated SVLBI time delay observables under the optimal observation condition, the estimation precision of CE-1 orbit can achieve a level of 2 m. On the other side, the precision of some *EOPs* components can be improved when compared with their predicted values by fixed remaining components as known values. The method discussed in this paper provides a new attempt of deep space probe orbit determination and *EOPs* estimation.

1. Introduction

Being the most accessible planetary body, the Moon has always been an important target of international deep space exploration. In addition, it is significant for deciphering the geological evolutionary history of solar system [1]. In recent years, with remarkable achievements made in the field of Earth satellites and manned space flights, China has been actively carrying out its autonomous deep space exploration projects. Up to now, Chang'E-1/2 and 3 (CE-1/2/3), the three important projects of China's Lunar Exploration, have been implemented successfully. A solid foundation has been laid for subsequent lunar science missions, such as lunar sample returning and so on.

During the lunar exploration, precise orbit determination of the probe is a key element due to its direct relation to various scientific experiments and applications, such as the lunar probe entering the mission orbit, global lunar image map, lunar DEM, lunar gravity field and so on. In CE-1 project, the unified s-band monitoring system (USB) and very long baseline interferometry (VLBI) were used for probe orbit determination, in which VLBI played an important role due to its high precision observations when the probe entered the transfer orbit. Current orbit accuracy of CE-1 is just 1–2 km during the transfer orbit and several hundred meters during the mission orbit, which would not meet the demand of high-precision applications, such as lunar geodesy [2–4]. Therefore, improving probe orbit determination pre-

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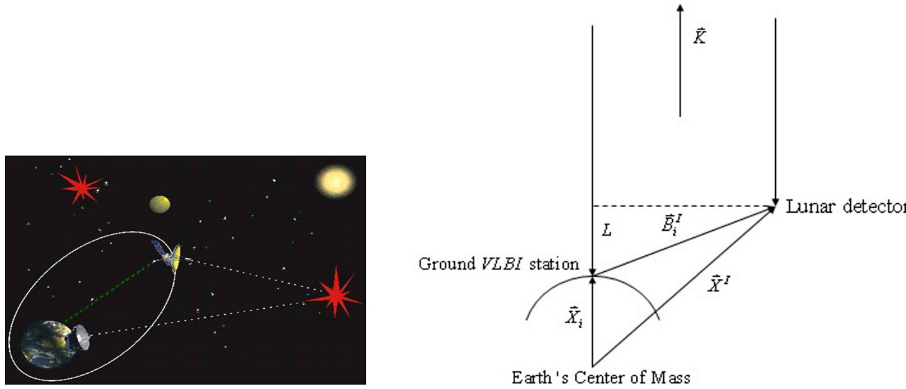

Fig. 1. Geometry of SVLBI observation.

cision has become a main challenge of China's Lunar Exploration Program.

To improve probe orbit determination precision, the Earth orientation Parameters (*EOPs*) and the relativistic effect corrections were introduced to the orbit determination of CE-1 by a derived differential VLBI (ΔVLBI) time delay mathematical model [5,6]. An important conclusion has been drawn that *EOPs* is crucial for lunar probe orbit determination and must be estimated because the priori precision of *EOPs* would cause an error of orbit estimation with a level of one hundred meters. As the consequence, the probe orbit parameters are simultaneously estimated with *EOPs* under CE-1 ground measurements, and the results showed that the precision of CE-1 orbital parameters and *EOPs* can be improved significantly when compared with their priori values by this method. Thus, a win–win approach of improving the precision of CE-1 orbital parameters and *EOPs* has been provided.

However, the precision of CE-1 ΔVLBI time delay measurements with just nanoseconds is still lower than the precision of traditional VLBI observables with picoseconds. As a result, the estimation precision of unknown parameters will be affected. On the other hand, geometry structure of CE-1 observables will be gradually deteriorated with the increase of the orbit altitude and some other problems exposed when the probe enters the mission orbit, such as the influence of lunar gravitational field, precise coordinate conversion between Earth system and Moon system, and so on. The above factors will make it difficult to obtain more precise orbit by ground ΔVLBI measurements under current observation condition, which will restrict further development of lunar exploration mission and must be resolved.

An intuitive idea is placing an antenna on a satellite in the sky, which means space very long baseline interferometry (SVLBI). SVLBI is an extension of ground based VLBI by observing stable extragalactic radio sources using VLBI telescopes mounted on the probe and on the ground respectively. Because the baseline of SVLBI may achieve a longer diameter than the Earth, more precise observables can be expected. Furthermore, SVLBI has advantages, such as improving the geometry structure of time delay observables, directly interconnecting three coordinate systems involved in geodesy and geodynamics including the terrestrial reference system, celestial reference system and dynamical reference system, calculating orbital parameters and *EOPs* simultaneously and so on [7]. So SVLBI can be attempted to improve the orbit determination of deep space probes. In this paper, the principal of SVLBI and its development status are introduced. Feasibility of the application of SVLBI in CE-1 orbit determination is analyzed. Mathematical model is derived, targeted experiments are implemented and some initial results are presented.

2. Space VLBI

The proposal of SVLBI can be traced back to 1970s. With the development of related theory and techniques, although it is difficult to mount a large antenna on a satellite, there still have been many international SVLBI projects by now, such as VSOP (Japan, 1997), RADIOASTRON (Russia, postponed), ARISE (USA, planning) and so on, in which VSOP is the 1st SVLBI satellite in human history [7,8]. These projects provided valuable data and experience for the development of SVLBI technology.

The principal of SVLBI is shown in Fig. 1. The time delay observables of SVLBI can be obtained by observing stable extragalactic radio sources using VLBI telescopes mounted on the deep space probe and on the ground, respectively. The propagation paths of signals from radio source to the two VLBI telescopes can be seen as parallel lines because radio source is too far away from two telescopes. So SVLBI time delay observables can be written as equation (1):

$$\tau = \tau_g + \Delta\tau = -\frac{1}{c}(\vec{B} \cdot \vec{K}) + \Delta\tau \qquad (1)$$

where τ_g indicates the geometrical time delay observables and $\Delta\tau$ denotes the non-geometrical time delay observables, including the effects of random error and systematic errors, such as solar radiation pressure, atmospheric refraction and so on, $\vec{B}$ is the baseline vector from ground VLBI station to lunar probe, $\vec{K}$ is the direction vector radio source signals, and c denotes the light speed.

Many researchers have studied the application of SVLBI in the field of geodesy. Adam (1990) [8] studied the estimability of geodetic parameters from SVLBI observables. Kulkarni (1992) [7] researched the feasibility of SVLBI for geodesy and geodynamics. SVLBI time delay observables were simulated by VSOP design orbit. And the model parameters, such as satellite orbital parameters and Earth Rotation Parameters (*ERP*), were estimated. Results have shown that the estimation precision of *ERP* can be improved by SVLBI compared with other geodetic technologies under precise priori information of parameters and the precise modeling of systematic influence. Zheng et al. (1993) [9–11] studied the establishment of reference systems and their connection using SVLBI. Wei (2006) [12] researched the design of Chinese SVLBI system and some simulated computation. These researches show that SVLBI has great potential for the application in geodesy. SVLBI would provide effective methods to overcome the problems involved in the orbit determination strategy of CE-1 using ground based ΔVLBI geometric observables. So it can be expected that the orbit determination precision of CE-1 will be further improved if SVLBI is applied in the orbit determination. In this paper, SVLBI time delay observables are simulated for CE-1 transfer