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A simulation of the Four-way lunar Lander–Orbiter tracking mode for the Chang'E-5 mission

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Abstract

The Chang'E-5 mission is the third phase of the Chinese Lunar Exploration Program and will collect and return lunar samples. After sampling, the Orbiter and the ascent vehicle will rendezvous and dock, and both spacecraft will require high precision orbit navigation. In this paper, we present a novel tracking mode—Four-way lunar Lander–Orbiter tracking that possibly can be employed during the Chang'E-5 mission. The mathematical formulas for the Four-way lunar Lander–Orbiter tracking mode are given and implemented in our newly-designed lunar spacecraft orbit determination and gravity field recovery software, the LUnar Gravity REcovery and Analysis Software/System (LUGREAS). The simulated observables permit analysis of the potential contribution Four-way lunar Lander–Orbiter tracking could make to precision orbit determination for the Orbiter. Our results show that the Four-way lunar Lander–Orbiter Range Rate has better geometric constraint on the orbit, and is more sensitive than the traditional two-way range rate that only tracks data between the Earth station and lunar Orbiter. After combining the Four-way lunar Lander–Orbiter Range Rate data with the traditional two-way range rate data and considering the Lander position error and lunar gravity field error, the accuracy of precision orbit determination for the Orbiter in the simulation was improved significantly, with the biggest improvement being one order of magnitude, and the Lander position could be constrained to sub-meter level. This new tracking mode could provide a reference for the Chang'E-5 mission and have enormous potential for the positioning of future lunar farside Lander due to its relay characteristic.

Keywords: Chinese Lunar Exploration Program; Chang'E-5 mission; Four way lunar Lander–Orbiter tracking; Precision orbit determination

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1. Introduction

The Chinese Lunar Exploration Program (CLEP) has entered into its third stage after the successful launches of the Chang'E-1, Chang'E-2, Chang'E-3, Chang'E-5T missions (Ouyang et al., 2010; Li et al., 2012; Jin et al., 2013; Xiao et al., 2015; Fan et al., 2015). China has gradually built up two kinds of tracking networks through these missions: the Chinese Deep Space Network (CDSN), including the Kashi and Jiamusi stations in China and a station in Argentina; and the Chinese Very Long Baseline Interferometry (VLBI) Network (CVN) including the Shanghai, Beijing, Kunming, and Urumqi stations (Huang et al., 2014; Liu et al., 2015). As a result, Chinese deep space tracking has advanced; the accuracy of the radiometric range, the Doppler measurement, and time delay for VLBI now reach 1 m, 1 mm/s (1 s integrated interval) and 1 ns, respectively (Fan et al., 2015). The Chang'E-5 Test mission (CE-5T) successfully tested the technology for returning from the Moon and high-speed

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re-entry into the Earth, paving the way for the upcoming Chang'E-5 sampling and return mission. In the Chang'E-5 mission scenario, there are four modules: a Lander, an ascent vehicle, an Orbiter, and a re-entry capsule. After surface sampling and encapsulation, the ascent vehicle will takeoff from lunar surface, and then make an automatic rendezvous and docking with the return module waiting in lunar orbit. For this mission to succeed, highly precise orbit information is required for in-orbit rendezvous and docking between the Orbiter and the ascent vehicle.

Since the beginnings of lunar exploration, various tracking modes have been developed. The SELENE' high–low satellite-to-satellite tracking (Namiki et al., 1999) and GRAIL' low–low satellite-to-satellite tracking modes (Lemoine et al., 2013) have improved our understanding of the lunar gravity field (Li et al., in press). The SELENE mission high–low satellite-to-satellite tracking mode demonstrated improved orbital accuracy for the main Orbiter. In this case, orbit accuracy of the main Orbiter was improved to almost a factor of two after including four-way high–low satellite-to-satellite tracking data and VLBI data, as the VLBI data is used to constrain the orbit of the relay satellite and thus permit the application of the four-way Doppler data (Goossens et al., 2011). As for the GRAIL's low–low satellite-to-satellite mode, the inter-spacecraft Ka-band range-rate (KBRR) data is accurate to near 0.03 μm/s and GRAIL orbits are determined to an accuracy of 20 cm (Konopliv et al., 2013). Some other tracking modes, such as the link between Earth stations, the lunar Orbiter and a fixed Lander, are also proposed to better constrain lunar tidal Love number in SELENE-2 mission (Sasaki et al., 2011, 2012). What's more, in order to study Mars rotational dynamics, triangular radio links between Landers, Orbiters, and the Earth are highly recommended and will be realized in the future geodesy mission for Mars (Kawano et al., 1999; Yseboodt et al., 2003; Dehant et al., 2009, 2011). Considering that the tracking mode based on this linkage could possibly be implemented in the following Chang'E-5 mission, in this paper we propose a new Four-way lunar Lander–Orbiter tracking mode specifically adapted for the Chang'E-5 mission.

Furthermore, we investigate the potential contribution of this new tracking mode to conventional lunar spacecraft orbit determination. We implemented simulation computation based on software we developed, the LUnar Gravity REcovery and Analysis Software/System (LUGREAS). This software was designed to deal with lunar spacecraft precise orbit determination and related lunar dynamic parameter resolution problems, including solving the lunar gravity field model coefficients and tidal deformation parameters using various types of tracking data. We compared our results with the Chang'E-1 precise orbit determination results based on GEODYN II to verify the reliability of our LUGREAS software (Yan et al., 2010, 2012).

This paper is organized as follows. Section 2 gives the mathematical model of the Four-way lunar Lander–Orbiter Range and Range Rate (4W L–O R&RR). In Section 3, we describe the simulated 4W L–O RR observables and discuss their contribution to precise orbit determination for the Orbiter by comparing with traditional two-way Earth tracking station and lunar Orbiter Range Rate (2W RR). A summary and conclusions are given in Section 4.

2. Mathematical model of Four way lunar Lander–Orbiter tracking measurement

This section briefly describes the measurement scenario, and provides the mathematical formulas of the computed values of the 4W L–O R&RR observables. In contrast to the traditional two-way approach, the 4W L–O tracking mode adds an extra link between the Lander and the Orbiter. As shown in Fig. 1, a transmitter frequency is sent from

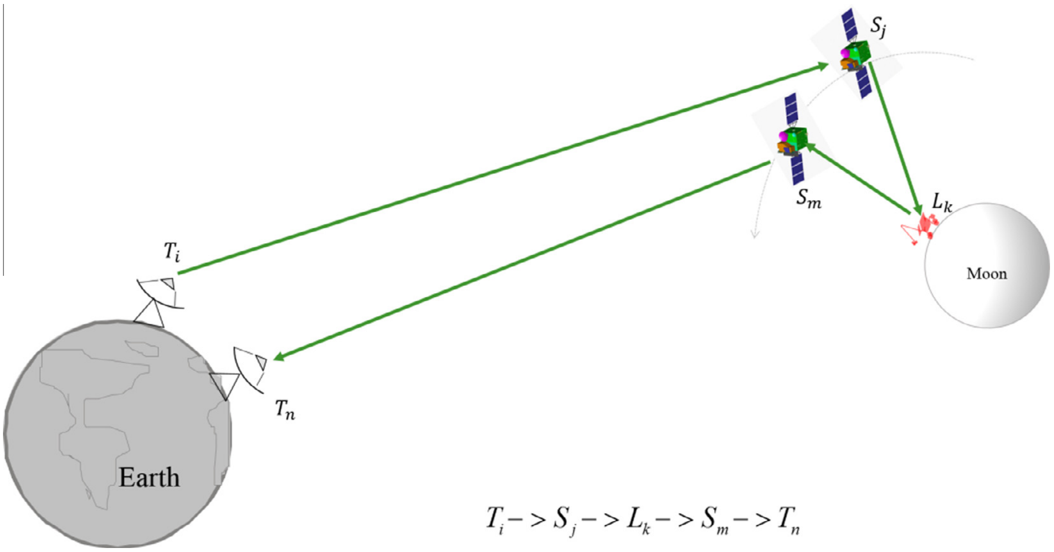

Fig. 1. Signal paths of the Four-way lunar Lander–Orbiter tracking mode.