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The shallow subsurface structures of Chang'E-3 landing site based on the wavefield characteristics of LPR Channel-2B data

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Abstract

The Lunar Penetrating Radar (LPR) carried by the Yutu rover has imaged the shallow subsurface of the Chang'E-3 (CE-3) landing site at the northern Mare Imbrium. In this paper, by processing LPR Channel-2B data we obtained radar waveform profile. According to the radar wavefield characteristics in the profile, three evident strata can be discovered in the lunar shallow subsurface below the CE-3 site. Most notably, many arc-shaped reflection and/or diffraction events are observed in the profile, especially more in the second layer. In order to find out what caused those arc-shaped events, we conducted radar wavefield numerical simulation. The numerical simulation results reveal that those arc-shaped events are most possibly resulted in by the rocks of different sizes and shapes from the craters surrounding the landing site, especially the C_1 crater.

Keywords: Moon; LPR waveform profile; Lunar shallow subsurface; Rocks

1. Introduction

Because of the continuous meteorite impact and the effects of the solar wind and the cosmic ray, the lunar shallow subsurface records the evolution history of the lunar surface environment (McKay et al., 1991; Fa and Jin, 2010). The knowledge of the structure and physical property of the lunar shallow subsurface may provide important information concerning the origin and evolution history of the moon (Ono et al., 2009). Also, the lunar shallow subsurface reserves a lot of mineral resources. Hence, the exploration of the lunar shallow subsurface not only increases humans' understanding of the moon, but also contributes to landing site determination for future manned lunar landing and exploitation and utilization of the lunar mineral resources.

Humans started to investigate the shallow subsurface structure of the Moon in the period of Luna missions. At that time, analyzing the lunar shallow subsurface was mainly based on observation of impact crater morphology and frequency distribution of the crater diameters (Oberbeck and Quaide, 1967, 1968; Shkuratov and Bondarenko, 2001). With the further exploration, more direct measurement methods were applied to investigate the lunar subsurface (Fa and Wieczorek, 2012). For example, the U.S. Apollo missions studied the lunar shallow subsurface structure and, specially, estimated the thickness of the regolith at Apollo 12, 14–17 landing sites using passive or active seismic method (Cooper et al., 1974; Nakamura et al., 1975). Another principal source of data about the lunar shallow subsurface is the regolith samples returned by both manned and unmanned missions to the

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Moon (McKay et al., 1991), showing that upper regolith of ~2 m deep is composed of numerous localized layers. But a limited number of samples, distributed at several insular sites, provided limited information of shallow subsurface structure.

Moreover, high frequency (HF) radar is an effective tool to image the lunar subsurface structures. In 1972, the lunar sounder experiment conducted by the scientific instrument module of the Apollo17 mission prospected the internal structures of the Moon (Phillips et al., 1973; Porcello et al., 1974; Peeples et al., 1978; Sharpton and Head, 1982). After that, the Kaguya Lunar Radar Sounder (Ono and Oya, 2000; Ono et al., 2008, 2009), Chandrayaan-1 Mini-SAR (Spudis et al., 2009, 2010), and LRO Mini-RF (Thomson et al., 2012; Spudis et al., 2013), mainly investigated the thickness of mare basalts and the existence of water ice.

The vertical resolutions of the early seismic and orbital radar data were rather low, ranging from tens to hundreds of meters. Therefore, they were not available for imaging the shallow subsurface structures in detail. However, the Lunar Penetrating Radar with the vertical resolution of ~30 cm in different frequency modes, carried by Yutu rover in Chinese CE-3 mission had a good opportunity to investigate the lunar internal structures on the lunar surface. It is able to characterize the fine structures of lunar regolith, which is an iconic achievement of studying the lunar subsurface.

The CE-3 LPR contains two channels whose basic parameters are shown in table 1. The Channel-1 was designed as monopole antennas, with dominant frequency of 60 MHz and resolution of meter level, and mounted on the rear of the rover. With working frequency ranging from 40 to 80 MHz, the Channel-1 can penetrate to a depth of over 100 m. The Channel-2 was mounted at the bottom of the rover, and it was only 273 mm above the lunar surface. It was designed as bow-tie dipole antennas with working frequency from 250 to 750 MHz and the dominant frequency of 500 MHz. The vertical resolution of the Channel-2 is less than 30 cm and its theoretical investigation depth is greater than 30 m. The Channel-2 consists of two receiving antennas, Channel-2A and Channel-2B. This study processed and analyzed the Channel-2B data.

Previous studies have reported different interfaces identified and interpretations of the shallow subsurface below the CE-3 site, based on LPR Channel-2B data (Xiao et al., 2015; Zhang et al., 2015; Fa et al., 2015). But all of those studies didn't analyze the wavefield characteristics of the radar waveform profile in detail. This paper discusses and focuses on the wavefield characteristics of LPR Channel-2B data in more detail and geological interpretation of these characteristics.

Table 1
Basic parameters of LPR.

Parameters	Channel-1	Channel-2
Center frequency (MHz)	60 MHz	500 MHz
Sampling interval (ns)	2.5 ns	0.3125 ns
Resolution	Meter level	<30 cm
Detection depth (m)	>100 m	>30 m

2. Data

The length of the rover track (Fig. 1) is ~114 m. The LPR collected data along the track from the position 1 to 16 in Fig. 1, but the Channel-2B data from the position 3–16 were selected in this study, because LPR worked in the test phase between the position 1–3 for seeking the best acquisition parameters.

Based on the operation mode of LPR, we performed data selecting, data splicing, removing delay time, and time adjustment to LPR raw data at first. Then, to improve the signal-to-noise ratio and resolution, after the above processing, we also processed the LPR data including amplitude compensation, filtering, deconvolution etc (Zhao et al., 2014). At last, the time-to-depth conversion was carried out for LPR profile from travel time vs. distance to depth vs. distance (Zhao et al., 2014). Fig. 2 is the processed result (Xiao et al., 2015) and our study of geological model is mainly based on this result.

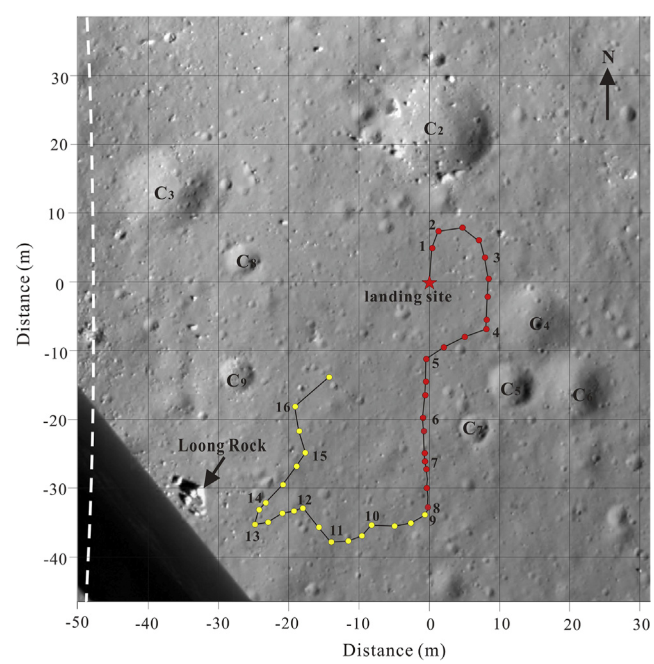

Fig. 1. The landing site of the Chang'E-3 and the track of the Yutu rover. The red star denotes the landing site of the CE-3. The red and yellow dots denote the positions on the Yutu rover track in the first and second lunar daytime, respectively. The dots marked by numbers denote the positions where LPR rebooted. The white dashed line denotes part of the rim of the C_1 crater. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)