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Spectroscopic observations of the Moon at the lunar surface

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ABSTRACT

The Moon's reflectance spectrum records many of its important properties. However, prior to Chang'E-3 (CE-3), no spectra had previously been measured on the lunar surface. Here we show the *in situ* reflectance spectra of the Moon acquired on the lunar surface by the Visible-Near Infrared Spectrometer (VNIS) onboard the CE-3 rover. The VNIS detected thermal radiation from the lunar regolith, though with much shorter wavelength range than typical thermal radiometer. The measured temperatures are higher than expected from theoretical model, indicating low thermal inertia of the lunar soil and the effects of grain facet on soil temperature in submillimeter scale. The *in situ* spectra also reveal that 1) brightness changes visible from orbit are related to the reduction in maturity due to the removal of the fine and weathered particles by the lander's rocket exhaust, not the smoothing of the surface and 2) the spectra of the uppermost soil detected by remote sensing exhibit substantial differences with that immediately beneath, which has important implications for the remote compositional analysis. The reflectance spectra measured by VNIS not only reveal the thermal, compositional, and space-weathering properties of the Moon but also provide a means for the calibration of optical instruments that view the surface remotely.

1. Introduction

Reflectance spectra, an important tool for exploring the Moon, are available in the form of laboratory measurements of lunar samples (e.g., Pieters et al., 2000), remote measurements from Earth-based telescopes (e.g., McCord et al., 1981; Lucey et al., 1986; Shkuratov et al., 2001; Kieffer and Stone, 2005; Saiki et al., 2008; Velikodsky et al., 2011) or spacecraft (e.g., Hillier et al., 1999; Besse et al., 2013; Wu et al., 2013; Ohtake et al., 2010; Boyd et al., 2012; Mahanti et al., 2016). These measurements are limited in their representation of the actual absolute reflectance of the Moon because of the disturbance of returned lunar regolith and the lack of an onboard calibration device. Reflectance spectra collected *in situ* with a calibration panel not only can quantify the absolute reflectance, but also have the potential to give more compositional detail and provide ground truth for remote sensing data. More uniquely, such data can provide key information on space weathering by measuring the undisturbed uppermost regolith as well as locations that have been affected by rocket exhaust from the spacecraft. The first *in situ* reflectance spectra was not measured until the end of 2013 when China's Chang'E-3 (CE-3) spacecraft landed on the Moon.

At 13:11:18 UTC on December 14 2013, CE-3 landed in the northern Mare Imbrium (Fig. 1) with the landing site at (44.1281°N, 19.5110°W). The landing site is ~50 m east of a 450 m crater named Zi Wei. The unit of the landing site belongs to the last major phase of lunar volcanism (Eratosthenian basalts) with an age newly dated as ~2.35 Ga (Wu et al., 2015). These unsampled basalts attracted significant attention quite a long time ago due to their relatively young age and unique spectra in terms of darkness, blue color, wide 1 μm absorption, and attenuated 2 μm absorption (e.g., Staid et al., 2011; Wu et al., 2015). A Visible-Near Infrared Spectrometer (VNIS) was carried on the "Yutu (Jade Rabbit)" rover and measured the first set of *in situ* reflectance spectra of the Moon. Early work on VNIS mostly focused on instrumental description/calibration (He et al., 2014; Xu et al., 2014; Liu et al., 2014) or mineral and elemental analyses (Zhang et al., 2015a, 2015b; Ling et al., 2015; Hu et al., 2015; Wang et al., 2017). In this paper we present a comprehensive analysis of the *in situ* reflectance spectra of the Moon.

2. The VNIS and *in situ* observations

The VNIS, one of the 4 main scientific payloads on the "Yutu" rover, was initially designed for the mineral detection on the lunar

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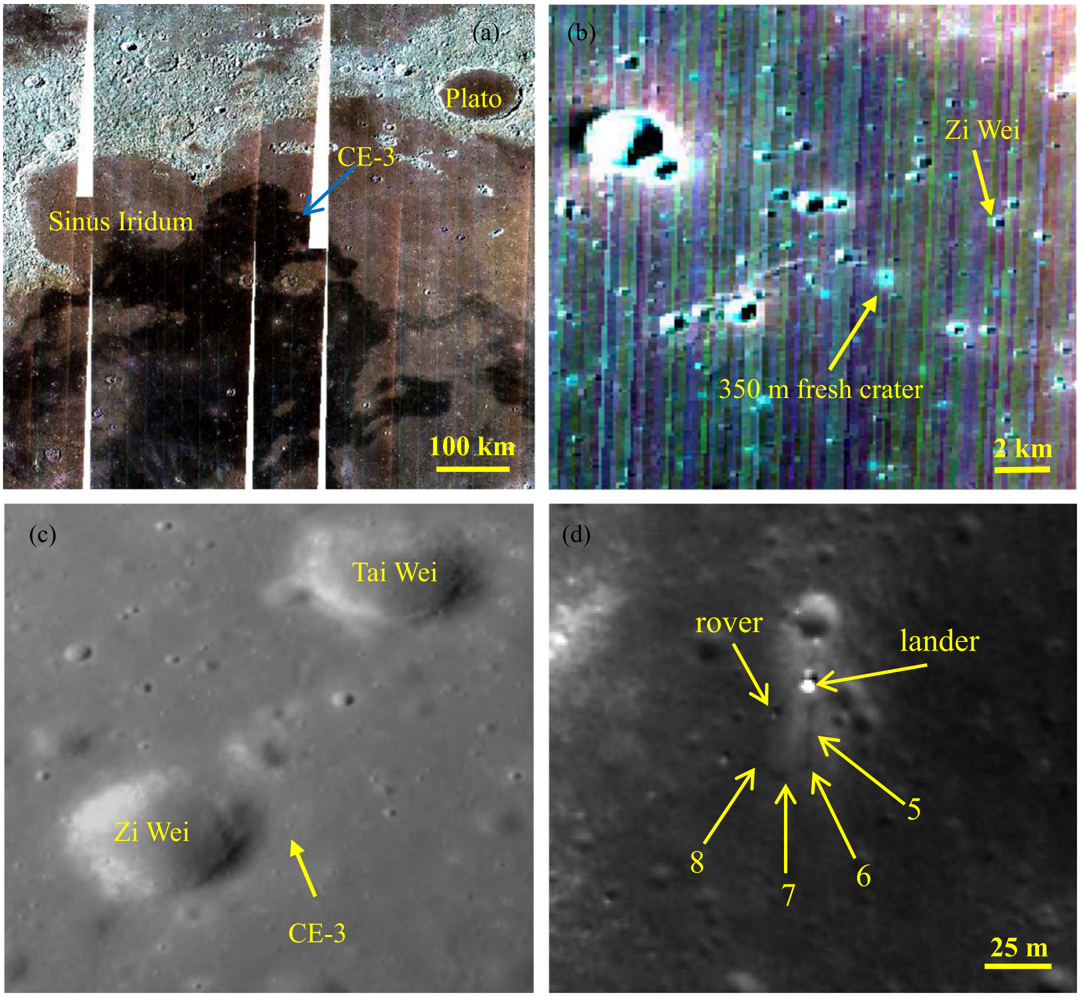

Fig. 1. Context images showing the location of the CE-3 landing site. (a) and (b) M^3 image. (c) CE-3 descent camera image. (d) LROC NAC image (M1147290066R). The locations of the four spectral measurements (numbered 5 to 8), the lander, the final position of the rover and the 350 m fresh crater are also shown.

Table 1
The performance characteristics of VNIS.

Description	Specification	
	VIS/NIR	SWIR
Observation zenith angle	45°	45°
Height above the surface (m)	0.69	0.69
Spectral range (nm)	450–950	900–2395
Spectral resolution (nm)	2–7	3–12
Field of View	8.5° × 8.5°	Φ3.6°
Effective pixel count	256 × 256	1
Bit resolution	10	16
Signal to Noise Ratio (dB)	31	32
Power consumption (W)	19.8	
Environment temperature	−20 °C to +55 °C	
Weight (kg)	4.7 (probe part) and 0.7 (electronics part)	

surface. Table 1 and Fig. 2 show its performance characteristics and schematic of detection, respectively. It uses acousto-optic tunable filters (AOTFs) as dispersive components and consists of a VIS/NIR imaging spectrometer, a shortwave IR (SWIR) spectrometer, and a white calibration panel that is protected from dust. The default spectral sampling interval is 5 nm, and the total number of sampling bands is 400 (100 bands for the VIS imaging spectrometer and 300 bands for the SWIR spectrometer; note that the bands between 900–945 nm overlap). The VNIS is mounted on the front of the rover and detects lunar surface objects from a height of 0.69 m above the lunar surface at 45° emission angle. The nominal spatial resolution of the VIS imaging spectrometer is 0.53–0.80 mm/p and the field of view (FOV) is an isosceles trapezoid with a height of 20.6 cm and two parallel sides of 13.5 cm and 15.7 cm. The field of view of the SWIR spectrometer is oval with diameter of 6.14 cm and 8.68 cm. The center of the SWIR corresponds to (X96, Y128) of VIS. To match the FOV of the VIS and SWIR bands, the VIS spectra is an average of a circle centered at the coordinate (96, 128) in the images, with a diameter of 108 pixels. When compared with the solar illumination, both the specular and diffuse reflection of the rover body on the calibration panel can be neglected because the panel is embedded in the rover body and the rover body right above it is coated black (Fig. 2b). When compared with the solar illumination, the diffuse reflection of the rover body on the lunar surface can also be neglected because most of the light is specular reflected out of the FOV of the VNIS.

A calibration unit (white standard panel), whose material is polytetrafluoroethylene (PTFE), was located at the light entrance; hence it functions as both a calibration reference and as a cover to exclude dust. Its directional-hemispherical reflectance (DHR), reflectance factor (REFF), and surface uniformity were measured and traced to the National Institute of Metrology (NIM), China. It is based on a standard diffusion screen that was tested by the NIM and uses an integrating sphere system with a double light path to set the standard. The uncertainty for DHR and REFF is 1.3% and 2.5%, respectively (He et al., 2014). Three modes were designed for the diffuser panel (Fig. 2b). When the spectrometer is in detection mode, it can be completely opened, and hence does not affect the entrance of light into the instrument. When the spectrometer is