Lunar absolute reflectance as observed by Chang'E-1 Imaging Interferometer

SCIENCE CHINA
Physics, Mechanics & Astronomy

SCIENCE CHINA
Physics, Mechanics & Astronomy

• Article •

August 2015 Vol. 58 No. 8: 089601
doi: 10.1007/s11433-015-5680-9

Lunar absolute reflectance as observed by Chang'E-1 Imaging Interferometer

ZHANG Jiang[1,2,3], LING ZongCheng[2,3*], LIU JianZhong[4], WU ZhongChen[2,3], LI Bo[2,3] & NI YuHeng[2,3]

[1] *School of Physics, Shandong University, Jinan 250100, China;*
[2] *Institute of Space Sciences, Shandong University, Weihai 264209, China;*
[3] *Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, School of Space Science, Shandong University, Weihai 264209, China;*
[4] *Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China*

Received November 25, 2014; accepted February 11, 2015

Lunar absolute reflectance, which describes the fraction of solar radiation reflected by the Moon, is fundamental for the Chang'E-1 Imaging Interferometer (IIM) to map lunar mineralogical and elemental distributions. Recent observations made by the Spectral Irradiance Monitor (SIM) onboard the Solar Radiation and Climate Experiment (SORCE) spacecraft indicate that temporal variation in the solar radiation might have non-negligible influence on reflectance calculation, and the SIM measurements are different from the two previously used solar irradiances, i.e., ATLAS3 and Newkur. To provide reliable science results, we examined solar irradiance variability with the SIM daily observations, derived lunar absolute reflectances from the IIM 2A radiance with the SIM, ATLAS3 and Newkur data, and compared them with the Chandrayaan-1 Moon Mineralogy Mapper (M^3), the Robotic Lunar Observatory (ROLO) and the Kaguya Multispectral Imager (MI) results. The temporal variability of the SIM solar irradiance is 0.25%–1.1% in the IIM spectral range, and less than 0.2% during the IIM observations. Nevertheless, the differences between the SIM measurements and the ATLAS3 and Newkur data can respectively rise up to 8% and 5% at particular IIM bands, resulting in discrepancy between which might affect compositional mapping. The IIM absolute reflectance we derived for the Moon using the SIM data, except for the last two bands, is consistent with the ROLO and the MI observations, although it is lower.

Chang'E-1, Imaging Interferometer (IIM), absolute reflectance, solar irradiance

PACS number(s): 78.40.Pg, 95.55.Qf, 96.20Dt

Citation: Zhang J, Ling Z C, Liu J Z, et al. Lunar absolute reflectance as observed by Chang'E-1 Imaging Interferometer. Sci China-Phys Mech Astron, 2015, 58: 089601, doi: 10.1007/s11433-015-5680-9

The Imaging Interferometer (IIM) is a multispectral imaging spectrometer onboard the Chang'E-1 spacecraft, and is designed to measure the solar radiation reflected by the Moon with 32 bands in the wavelength range between 480 and 960 nm, aiming to map lunar surface mineralogical and elemental distributions [1]. The IIM raw data have been converted into reflectance with the laboratory measurement of the Apollo 16 62231 lunar soil [2–4], and corrected with the Earth-based telescopic observations [2,4], all of which were based on the method developed in the Clementine UVVIS calibration [5]. Recent studies suggest that the remotely measured reflectance values for surface soils might significantly differ from those for sample soils measured in the laboratory, as texture and microstructure of the returned Apollo lunar soils had been inevitably altered during sampling processes [6,7]. Thereafter, the IIM absolute reflec-

*Corresponding author (email: zcling@sdu.edu.cn)

tance has been derived recently with the ATLAS3 solar spectral irradiance [8]. While the ATLAS3 data, like the Newkur data formerly used in lunar studies [9], were measured prior to the Chang'E-1 mission [10], the new daily solar observations by the Solar Radiation and Climate Experiment (SORCE) Spectral Irradiance Monitor (SIM) (http://lasp.colorado.edu/sorce) enable us to derive lunar absolute reflectance with the solar irradiance measured at the IIM observation times, and to estimate the role of various solar irradiances in reflectance calculation.

1 Method

1.1 IIM 2A data

During the Chang'E-1 mission between October 2007 and March 2009, the IIM acquired a total of 706 orbits of images that cover 85% of the lunar surface between 75°S and 75°N at a spatial resolution of 200 m/pixel [1], out of which 566 orbits obtained in the mid-2008 (Figure 1). The IIM raw data were calibrated into the Level 2A 32-band radiance between 480 and 960 nm at a spectral resolution of 325.5 cm^{-1} (equivalent to 7.6–29 nm in wavelength), through radiometric calibration pipeline developed based on the preflight laboratory measurements [11].

To accurately identify diagnostic absorption features of lunar surface minerals, the IIM 2A radiance data have to be processed into reflectance with solar irradiance measurements [5], so as to eliminate spectral features related to the incident sunlight on the lunar surface. The processing procedure involves two steps, i.e., Sun-Moon distance correction and reflectance calculation.

1.2 Solar distance correction

Lunar surface radiance I_D, measured by the IIM at Sun-Moon distance D, is proportional to the incident solar irradiance J_D [12]; meanwhile, J_D is inversely proportional to D^2 in geometric optics [13]. Since solar irradiances are reported at a mean solar distance of 1 Astronomical Unit (AU) [14], the IIM 2A radiance I_D also has to be corrected into those ($I_{1\,\mathrm{AU}}$) at a standard Sun-Moon distance of 1 AU by eq. (1):

$$\frac{I_{1\,\mathrm{AU}}}{I_D} = \frac{J_{1\,\mathrm{AU}}}{J_D} = \left(\frac{D}{1\,\mathrm{AU}}\right)^2 = D^2, \tag{1}$$

where D is the Sun-Moon distance in AU.

The Sun-Moon distance D in eq. (1) was calculated for each pixel of the IIM 2A images from the IIM latitude/longitude data and observation times for each image line, with the NASA NAIF SPICE Toolkit and SPICE kernels naif0010.tls, pck00010.tpc, and DE430.bsp (http://naif.jpl.nasa.gov), which is recommended for use in lunar data analysis [15]. The mean Sun-Moon distance D and the corresponding correction factor D^2 in eq. (1) for each orbit of the IIM 2A data are shown in Figure 2, in which the correction factor is from 0.97 to 1.04, while the variation of D and the corresponding correction factor D^2 in each IIM orbit are both less than 0.01%.

1.3 Reflectance calculation

Sun-Moon distance for each orbit of the IIM 2A data and correction factor are used to correct the IIM 2A radiance to those at a standard Sun-Moon distance of 1 AU. After corrected into radiance at a standard Sun-Moon distance of 1 AU, the IIM radiance data still contain spectral features related to the incident sunlight, and should be converted into reflectance to remove these features, before the data can be used to identify lunar surface minerals [5]. For convenience, we derived lunar surface reflectance as radiance factor (RADF) [12], which is dimensionless and has been used by other recent lunar measurements such as USGS Robotic Lunar Observatory (ROLO), Kaguya Multispectral Imager

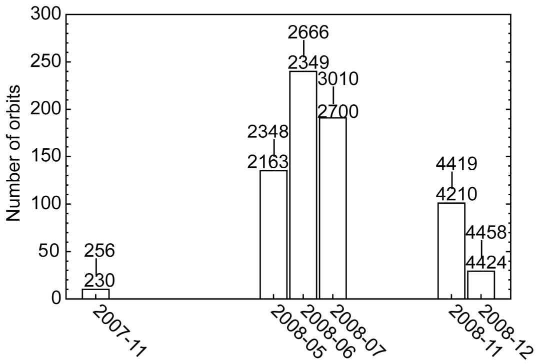

Figure 1 Data statistics for each month during the Chang'E-1 IIM observations, with orbit number range on the top of each histogram bin.

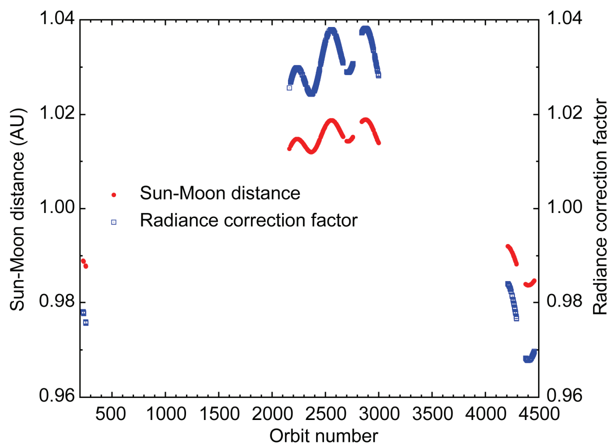

Figure 2 (Color online) Sun-Moon distance for each orbit of the IIM 2A data and correction factor used to correct the IIM 2A radiance to those at a standard Sun-Moon distance of 1 AU.

(MI), and Chandrayaan-1 Moon Mineralogy Mapper (M^3) [9]:

$$\mathrm{RADF} = \pi \frac{I_{1\,\mathrm{AU}}}{J_{1\,\mathrm{AU}}}, \quad (2)$$

where $I_{1\,\mathrm{AU}}$ and $J_{1\,\mathrm{AU}}$ are the IIM radiance and solar irradiance at a standard Sun-Moon distance of 1 AU, respectively.

Two solar irradiance datasets have been used in recent lunar studies, i.e., ATLAS3 and Newkur [8,9], both of which were measured prior to the Chang'E-1 mission and did not take temporal variations into consideration [10]. The recent SORCE SIM observations obtained daily solar irradiance in the visible and near-infrared spectral region with absolute accuracy better than 2% [16] from 2003–2011, providing us an opportunity to estimate solar temporal variability and to derive lunar absolute reflectance from the IIM 2A radiance data with real-time solar irradiance measurements during the Chang'E-1 mission. As shown in Figure 3, the temporal variability, which is defined by eq. (3) below, is dependent on wavelength, and is 0.25%–1.1% in the IIM spectral range from 2003–2011, and is down to less than 0.2% during the IIM observation times.

$$\mathrm{Variability} = \frac{J_{\mathrm{Maximum}} - J_{\mathrm{Minimum}}}{J_{\mathrm{Minimum}}} = \frac{J_{\mathrm{Maximum}}}{J_{\mathrm{Minimum}}} - 1. \quad (3)$$

To derive lunar absolute reflectance with eq. (2), the daily solar irradiance spectra measured by the SORCE SIM during the IIM observation times were resampled into the IIM bandpasses, along with the ATLAS3 and Newkur datasets used in other lunar studies for comparison [8,9]. As shown in Figure 4, for most of the IIM bands, the ATLAS3 and Newkur irradiances are higher than the SIM values; the differences between the SIM and ATLAS3 or Newkur data can respectively rise up to 5% and 8% at particular IIM bands (480–650 nm, as shown in the inset of Figure 4(a)) in the visible spectral region. Therefore, these discrepancies would lead to non-negligible errors in absolute reflectance calculation.

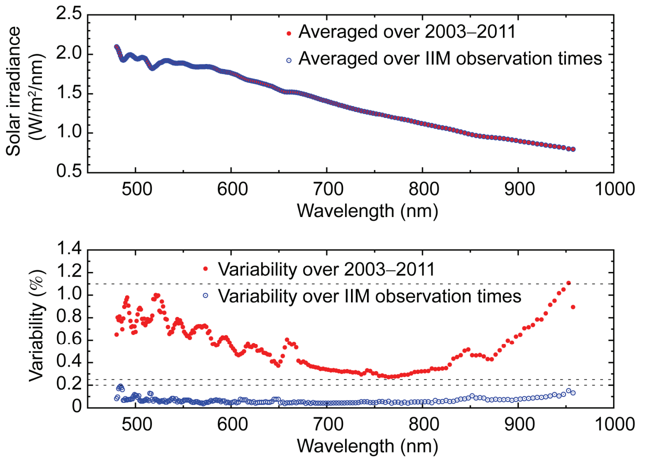

Figure 3 (Color online) SORCE SIM averaged solar irradiances and their temporal variabilities over 2003–2011 and over the Chang'E-1 IIM observation times.

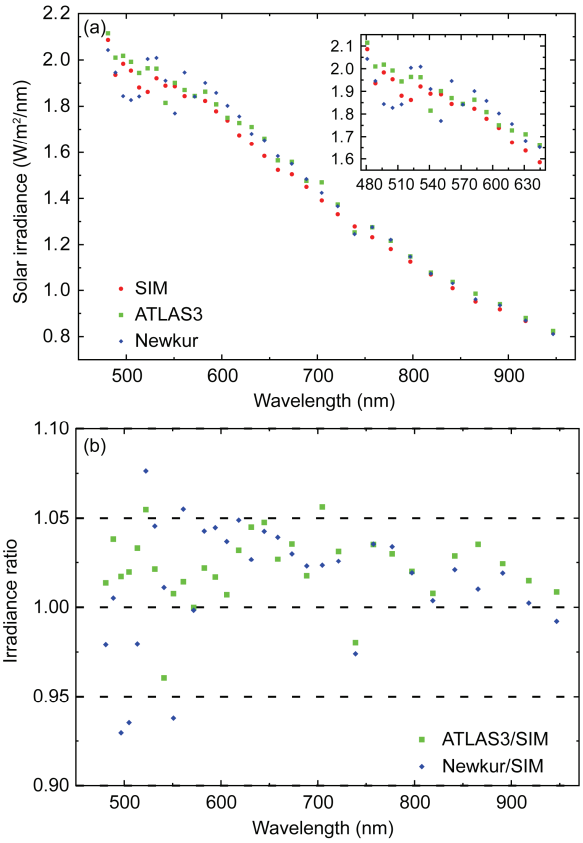

Figure 4 (Color online) Solar irradiances (SIM, ATLAS3, and Newkur) resampled at the IIM bands (a) and ratios (b).

2 Results

We calculated the IIM absolute reflectances respectively with the resampled SIM, ATLAS3 and Newkur solar irradiances by the method described above. In order to achieve reliable scientific results, the derived reflectances were validated at the Apollo 16 standard site and an area in Mare Serenitatis. The Apollo 16 standard site (15°E, 9°S) has been extensively used as an optical standard in previous Earth-based telescopic and remote-sensing observations such as the Clementine UVVIS, USGS ROLO, Kaguya MI, and Chandrayaan-1 M^3 [5,9]. The undisturbed mare soils in Mare Serenitatis have been also often used as a calibration standard, and could be used as additional reflectance reference [9]. Both areas were covered by the Chang'E-1 IIM observations (Figure 5).

As shown in Figure 6, the IIM absolute reflectances derived from the three solar irradiances all appear to have a similar spectral trend. As expected from eq. (2) and Figure 4,

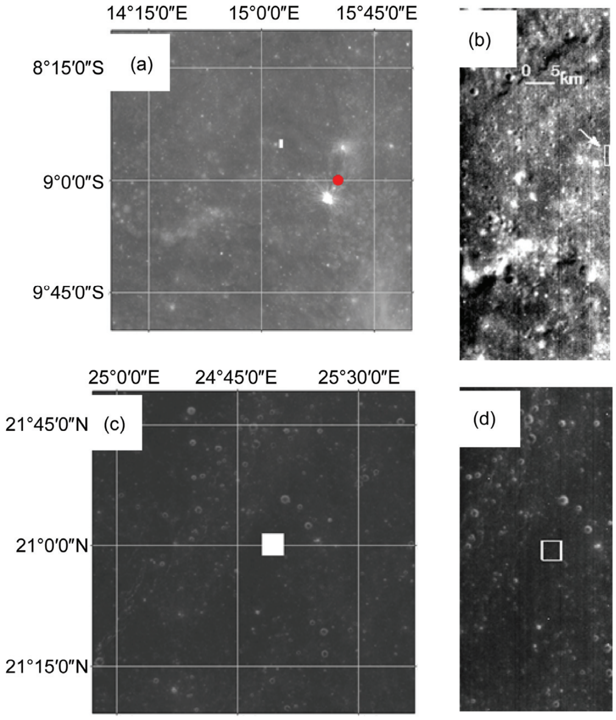

Figure 5 (Color online) Apollo 16 (a), (b) and Mare Serenitatis (c), (d) standard sites in Chang'E-1 CCD (500–750 nm) (a), (c) and IIM Band 24 (757 nm) (b), (d) images. The Apollo 16 landing site is marked by red spot in (a). Area location for Apollo 16 site: IIM Orbit 2225, Sample 124–128, Line 11117–11131; Area location for Mare Serenitatis site: IIM Orbit 2217, Sample 70–86, Line 6723–6739.

the absolute reflectances derived with the ATLAS3 and Newkur irradiances are lower than that with the SIM data for most of the IIM bands. Larger differences occur in the IIM visible spectral region (<600 nm), e.g., the IIM Band 6 (522 nm) deviations of 0.95 (ATLAS3) and 0.93 (Newkur) from the SIM results (Figures 6(b) and (d)). These deviations due to different solar irradiances could affect subsequent compositional mapping [17].

As shown in Figure 7, we compared the SIM-derived IIM absolute reflectances for the Apollo 16 and Mare Serenitatis standard sites with the Kaguya MI, USGS ROLO, and Chandrayaan-1 M^3 data (Table 1), in which the photometrically corrected IIM reflectacnes (i=g=30°, e=0°) were derived with an empirical Lommel-Seeliger function [18] The IIM absolute reflectances of both sites are in general consistent with those measurements acquired by the other three instruments, when considering their calibration uncertainties (Table 2). Differences in absolute reflectance values are observed, although their spectral trends are similar. The IIM and M^3 values are both lower than those of the ROLO and MI, probably caused by their higher spectral resolution although instrument artifacts might not be neglected. In addition, as discussed above, the SIM-derived IIM reflectance values are higher than those derived from the ATLAS3 and Newkur, thus closer to the ROLO and MI results. For highland (Apollo 16) and mare (Mare Serenitatis) soils, the IIM exhibits different behaviors, the reflectance value of mare is much closer to the ROLO and MI results than those for highland, although both are lower, likely due to residual IIM calibration errors. The Apollo 16 and Mare Serenitatis sites are covered by mature soils with ~1.0 μm weakened spectral features caused by space weathering effect, thus the last two IIM bands (918 and 946 nm) are obviously erroneous, beyond the uncertainty of 15% expected from preflight calibration (Table 2). The IIM

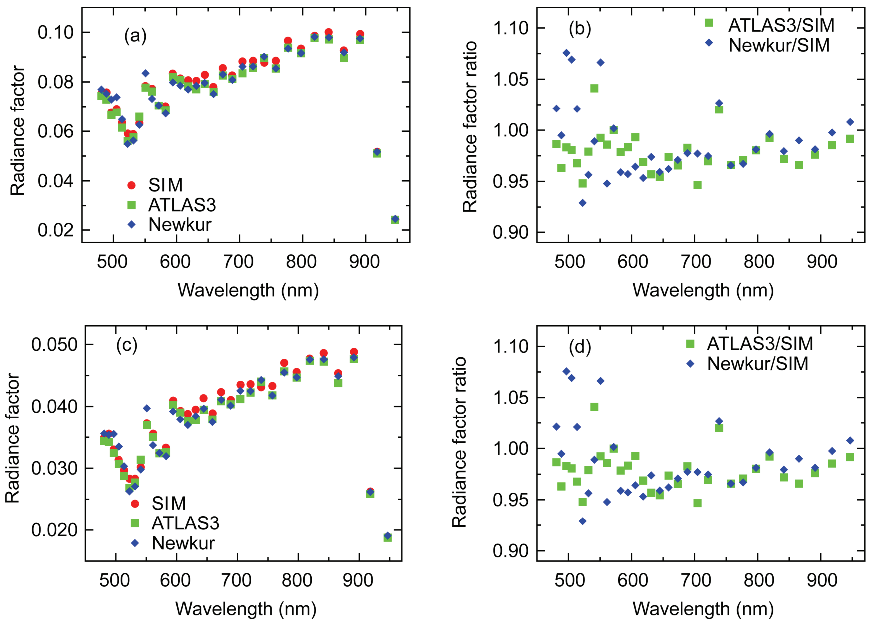

Figure 6 (Color online) Radiance factors and their ratios for the Apollo 16 standard site (a), (b) and Mare Serenitatis (c), (d) derived with the SIM, ATLAS3, and Newkur solar spectral irradiances.

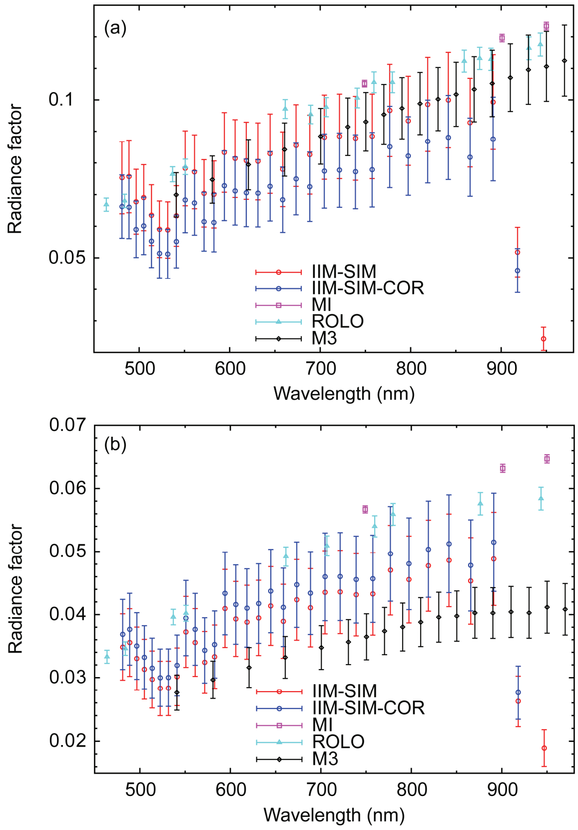

Figure 7 (Color online) Chang'E-1 IIM RADF at Apollo 16 standard site (a) and Mare Serenitatis (b) based on the SIM irradiance, comparing with ROLO, MI, and M^3 results. The calibration uncertainties are given in Table 2. The 'IIM-SIM-COR' RADF is photometrically corrected to standard geometry.

Table 1 MI, M^3 and IIM data for the Apollo 16 and Mare Serenitatis sites [7] (the IIM incidence/emission/phase angles are denoted by (i, e, g))

Instrument	Site	Image name/Orbit number
MI	Apollo 16	MI_MAP_02_S08E015S09E016SC
	Serenitatis	MI_MAP_02_N20E024N21E025SC
M^3	Apollo 16	M3G20090108T044645_V01_RFL
	Serenitatis	M3G20090203T200051_V01_RFL
IIM	Apollo 16	Orbit 2225 (28.7°, 5.8°, 23.3°)
	Serenitatis	Orbit 2217 (33.3°, 1.0°, 32.5°)

Table 2 Calibration uncertainties for the ROLO, MI, IIM, and M^3 data

Instrument	Uncertainties (%)	Reference
ROLO	3.1	[19]
MI	1	[20]
IIM	15	[21]
M^3	10	[22]

bands in the spectral range of 480–600 nm, which are essential for capturing characteristic visible absorption features, exhibit similar but smaller systematic artifacts that require further calibration efforts [23].

3 Conclusion

The lunar surface reflectance observed by the Chang'E-1 IIM is essential for us to yield plausible results such as elemental and mineralogical distributions. We examined the differences between three solar irradiances, i.e., SORCE SIM, ATLAS3, and Newkur, and their influences on the IIM absolute reflectance calculation. The SIM-derived reflectance is preferred in that it can reduce the spectral anomalies (e.g., IIM Band 6 @522 nm) due to incident solar radiation, and is closer to the Kaguya MI, USGS ROLO results than those reflectances derived from the ATLAS3 and Newkur data. In addition, the SORCE SIM daily solar irradiances are nearly real-time observations during the Chang'E-1 IIM operation periods, making it more compatible for the IIM reflectance calculation. The SIM-derived IIM absolute reflectances are validated at the Apollo 16 and Mare Serenitatis standard sites, showing that the IIM results for both sites are in general lower but consistent with those measurements acquired by the Kaguya MI, USGS ROLO, and Chandrayaan-1 M^3 when their calibration uncertainties are considered.

However, some IIM bands show large discrepancies with other measurements, indicating that further calibration efforts are needed. Future work will focus on reducing the residual instrument artifacts and photometric correction. As the first Chinese lunar mission, Chang'E-1 IIM acquired reliable reflectance data for lunar studies, and the experiences in the IIM data processing might help us better understand lunar absolute surface reflectance and provide some hints for reflectance calibrations of optical payloads onboard the ongoing Chang'E-3 mission and so on.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11003012, 41373068, 41473065 and U1231103).

1 Ouyang Z Y, Li C L, Zou Y L, et al. The primary science result from Chang'E-1 probe (in Chinese). Sci China-Earth Sci, 2010, 40: 261–280
2 Wu Y Z, Xu X S, Xie Z D, et al. Absolute calibration of the Chang'E-1 IIM camera and its preliminary application (in Chinese). Sci China Ser G-Phys Mech Astron, 2009, 39: 1387–1392
3 Chen C, Qin Q M, Zhang N, et al. Research on photometric calibration and reflectance calculation of CE1 IIS data (in Chinese). Spectrosc Spect Anal, 2011, 31: 1985–1990
4 Hu S, Lin Y T. Modified calibration method of the Chang'E-1 IIM images (in Chinese). Sci Sin-Phys Mech Astron, 2011, 41: 879–888
5 Pieters C M. The Moon as a spectral calibration standard enabled by lunar samples: The Clementine example. New Views of the Moon 2: Understanding the Moon Through the Integration of Diverse Datasets. 1999, 1: 47
6 Ohtake M, Matsunaga T, Yokota Y, et al. Deriving absolute reflectance of lunar surface using SELENE (Kaguya) Multiband Imager data. Space Sci Rev, 2010, 154: 57–77
7 Pieters C M, Boardman J W, Ohtake M, et al. One Moon, many measurements 1: Radiance values. Icarus, 2013, 226: 951–963
8 Wu Y Z, Besse S, Li J Y, et al. Photometric correction and in-flight

calibration of Chang'E-1 Interference Imaging Spectrometer (IIM) data. Icarus, 2013, 222: 283–295
9 Ohtake M, Pieters C M, Isaacson P, et al. One Moon, many measurements 3: Spectral reflectance. Icarus, 2013, 226: 364–374
10 Gueymard C A. The sun's total and spectral irradiance for solar energy applications and solar radiation models. Solar Energy, 2004, 76: 423–453
11 Zhao B C, Yang J F, Xue B, et al. Calibration of Chang'E-1 satellite Interference Imaging Spectrometer (in Chinese). Acta Photon Sin, 2010, 39: 769–775
12 Hapke B. Theory of Reflectance and Emittance Spectroscopy. Cambridge: Cambridge University Press, 2012
13 Born M, Wolf E. Principles of Optics. Cambridge: Cambridge University Press, 1999
14 Thuillier G, Loyd L, Woods T N, et al. Solar irradiance reference spectra. In: Pap J M, Fox P, eds. Solar Variability and its Effects on Climate, Geophysical Monograph. Washington DC: American Geophysical Union, 2004. 171–194
15 Folkner W M, Williams J G, Boggs D H, et al. The planetary and lunar ephemerides DE430 and DE431. IPN Progress Report 42-196, 2014
16 Harder G W, Thuillier G, Richard E C, et al. The SORCE SIM solar spectrum: Comparison with recent observations. Solar Phys, 2010, 263: 3–24
17 Ling Z C, Zhang J, Liu J Z, et al. Preliminary results of TiO_2 mapping using Imaging Interferometer data from Chang'E-1. Chin Sci Bull, 2011, 56: 2082–2087
18 Zhang J, Ling Z C, Zhang W X, et al. Photometric modeling of the Moon using Lommel-Seeliger function and Chang'E-1 IIM data. Chin Sci Bull, 2013, 58: 4588–4592
19 Kieffer H H, Stone T C. The spectral irradiance of the Moon. Astron J, 2005, 129: 2887–2901
20 Kodama S, Ohtake M, Yokota Y, et al. Characterization of multiband imager aboard SELENE: Pre-flight and in-flight radiometric calibration. Space Sci Rev, 2010, 154: 79–102
21 Qiu Y H, Zhao B C, Zhao J K, et al. Field performance test experiments of the Interference Imaging Spectrometer of Chang'E-1 satellite (in Chinese). Acta Photon Sin, 2009, 38: 484–488
22 Green R O, Pieters C M, Mouroulis P, et al. The Moon Mineralogy Mapper (M^3) imaging spectrometer for lunar science: Instrument description, calibration, on-orbit measurements, science data calibration and on-orbit validation. J Geophys Res, 2011, 116: E00G19
23 Ling Z C, Zhang J, Wu Z C, et al. The spectral calibration of Chang'E-1 IIM Dataset. In: The Proceedings of 45th Lunar and Planetary Science Conference. Texas: Lunar and Planetary Institute, 2014. 1831