One Moon, Many Measurements 3: Spectral reflectance

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\section*{Abstract}
Remote-sensing datasets obtained by each instrument aboard Selenological and Engineering Explorer (SELENE) and Chandrayaan-1 have not been compared directly, and the characteristics of each instrument's data, which may reflect the observation conditions of each instrument and/or residual error in instrument calibration, are unknown. This paper describes the basic characteristics of the data derived by each instrument, briefly describes the data-processing conversion from radiance to reflectance, and demonstrates what we can achieve by combining data obtained by different instruments on different missions (five remote-sensing instruments and an Earth-based telescope). The results clearly demonstrate that the spectral shapes of the instruments are comparable and thus enable us to estimate the composition of each geologic unit, although absolute reflectances differ slightly in some cases.

\section*{1. Introduction}
Recent successes of lunar exploration missions further our understanding of the Moon by analyzing the spectral reflectance of the lunar surface measured by a variety of instruments (Haruyama et al., 2008a; Ohtake et al., 2009; Matsunaga et al., 2008; Pieters et al., 2009a; Mall et al., 2009). We can derive more information by combining data obtained by different missions because each instrument on the Selenological and Engineering Explorer (SELENE) and Chandrayaan-1 spacecraft has different advantages (e.g., spatial and spectral resolution, and spectral coverage). Because reflectance data are widely used for compositional analyses, comparing data obtained by different instruments is important for evaluating and understanding variations among instrument datasets. However, combining data obtained by different instruments with confidence is not simple because each dataset was obtained under different observation conditions (e.g., incidence (i), emission (e), or phase angle (g)) and with different spatial (and spectral) resolutions. Differences in calibration procedures and the quality of each instrument are additional factors.

This paper summarizes the basic characteristics of reflectance data derived by each instrument and briefly describes the data-processing conversion from radiance to reflectance. Several examples of combined data demonstrate what can be achieved by integrating data obtained by different instruments on different missions. This information will be useful to all in the science community who use data acquired by different instruments for their research.

\section*{2. Derivation of reflectance spectra}
Table 1 summarizes the data-processing procedure used for each instrument's data to derive final reflectance values, which the instrument team then provides to the community. As described in Table 1, each instrument requires different data-correction steps according to the characteristics of that instrument. The following sections describe the procedures for each instrument. A companion paper by Pieters et al. (2013) described the hardware design of each instrument and the data processing from raw data to radiance. Therefore, only a brief description of each instrument required for understanding the data-processing procedures to derive reflectance from radiance is included in this paper.
Table 1
Summary of steps involved in converting radiance to reflectance.

<table>
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<th>MI</th>
<th>SP</th>
<th>M*</th>
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<tr>
<td>1. Divided by solar irradiance and corrected by solar distance</td>
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<td>2. Photometric correction (average of highland and mare coefficient results; with local topography)</td>
<td>2. Photometric correction (two datasets are included: highland and mare coefficient results; without local topography)</td>
<td>2. Photometric correction (highland model; with local topography)</td>
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SIR-2

| 1. Divided by solar irradiance and corrected by solar distance | 1. Divided by solar irradiance and corrected by solar distance |
| 2. Photometric correction (Shkuratov model) without local topography and Savitzky–Golay filter correction | 2. Lommel–Seelinger limb-darkening photometric correction |

| SPECTRAL PROFILES | 1. Divided by solar irradiance and corrected by solar distance |
| ROLO | 2. Photometric correction (average of highland and mare coefficient results; with local topography) |
| TC | 2. Photometric correction (McEwen model) |

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2.1. Multiband Imager

The Multiband Imager (MI) is a high-resolution, multiband imaging camera carried on SELENE and consists of separate visible and near-infrared sensors with five visible (415, 750, 900, 950, and 1000 nm) and four near-infrared (1000, 1050, 1250, and 1550 nm) bands. The swath widths of the visible and near-infrared bands are designed to be the same (19.3 km from SELENE’s nominal 100 km altitude). MI acquires push-broom imaging data. The spatial resolution of the visible bands is 20 m, and that of the near-infrared bands is 62 m from a nominal altitude. See Haruyama et al. (2008b), Ohtake et al. (2008, 2010), Kodama et al. (2010), and Takayama et al. (2011) for detailed discussions of MI properties and calibration.

In Step 1 of the data-processing procedure, the radiance data is divided by the solar irradiance and corrected by the solar distance. The solar irradiance is a solar spectrum resampled from MODTRAN4 (Gueymard, 2004) at MI wavelength. Step 2 is normalization to a standard geometry \((i = 30^\circ, e = 0^\circ, g = 30^\circ)\) using a photometric function based on the observation geometry. We adopted the photometric function described by Shkuratov et al. (1999) and its parameters are used.

2.2. Spectral Profiler

The Spectral Profiler (SP) is a nadir-looking, visible to near-infrared line-profiling spectrometer carried on SELENE. The spectral range of SP observations is 500–2600 nm, though in this paper we discuss data with the range of 500–1700 nm with 162 spectral channels (without overlap). The footprint of SP is 500 × 500 m. See Haruyama et al. (2008b), Matsunaga et al. (2001), Yamamoto et al. (2011), and Yokota et al. (2011) for detailed discussions of SP properties and calibration.

In Step 1 of the data-processing procedure, the radiance data is divided by the solar irradiance and corrected by the solar distance. The solar irradiance is a solar spectrum resampled from MODTRAN4 (Gueymard, 2004) at SP wavelength. Step 2 is normalization to a standard geometry \((i = 30^\circ, e = 0^\circ, g = 30^\circ)\) using a photometric function based on the observation geometry. We adopted the photometric function described by McEwen (1996) with the parameters of Yokota et al. (2011) for each wavelength using a spherical lunar topographic model. Two datasets are included, the highland and mare coefficient results of Yokota et al. (2011). The reflectance after this correction is presented as the reflectance (without “final”) in this paper. Step 3 is a ground-truth correction, which adjusts the SP spectra (both the absolute albedo and the slope) of the Apollo 16 standard site to a laboratory-measured spectrum of Apollo 16 soil 62231 (Yamamoto et al., 2011). The correction adjusts the spectral shape and gain, which changes the absolute albedo and the continuum slope. The location of the Apollo 16 standard site is described in Section 3.1. The correction is NOT applied to the delivered level 2C (reflectance) data, but the reflectance after this correction is presented for comparison in this paper.

2.3. Moon Mineralogy Mapper

The Moon Mineralogy Mapper (M*) is a push-broom imaging spectrometer carried on Chandrayaan-1. It uses a single two-dimensional detector that is sensitive across the visible and near-infrared wavelengths (spectral range from 460 to 3000 nm). The system produces “image cubes” of data consisting of two spatial dimensions and one spectral dimension. M* has a high-resolution mode (600 spatial elements with 260 spectral elements) and a low-resolution mode (300 spatial elements and 85 spectral elements). See Pieters et al. (2009b), Green et al. (2011), Boardman et al. (2011), and Lundeen et al. (2011) for detailed discussions of...
M² properties and calibration. All datasets discussed in this paper were acquired in the low-resolution ("global") mode.

In Step 1 of the data-processing procedure, the radiance data is divided by the solar irradiance and corrected by the solar distance. The solar irradiance is a solar spectrum resampled from MODTRAN4 (Gueymard, 2004) at M² wavelengths. Step 2 is statistical polishing to remove remaining systematic spectral artifacts and is a gain-only correction. Step 3 is thermal removal (an iterative function). This correction involves projection from shorter wavelengths into the thermal emission region, and removal of an “excess” signal assumed to be thermally emitted radiation. This procedure removes most (but not necessarily all) of the thermal component. Full details are presented in the M² PDS SIS (Lundeen et al., 2011) and by Clark et al. (2011). Step 4 is a photometric correction based on a Lommel–Seeliger model to a standard geometry (i = 30°, e = 0°, and g = 30°) using local topography (derived from available LOLA data). The correction parameters are calculated from highland data collected in a month of contiguous data (OP2C) covering g from 0° to 100°, fitted with a polynomial function in g, and smoothed in wavelength (see Besse et al., 2013a). Step 5 is a ground-truth correction to improve the consistency and accuracy of the 1 μm ferrous absorption feature using the spectral properties of laboratory data for mature highland soils. The correction adjusts the spectral shape without affecting the absolute albedo or continuum slope and is derived only for wavelengths below 1500 nm (see Isaacson et al., 2013 for examples). The ground-truth corrections are delivered with M² archive data but are NOT applied to the delivered level 2 (reflectance) data. These correction factors are strongly recommended for M² data and can be obtained at http://pds-imaging.jpl.nasa.gov/data/m3/CH1M3_0004/CALIB/.

2.4. Short-wave near-infrared grating spectrometer

The shortwave near-infrared Grating Spectrometer (SIR-2) is a nadir-looking near-infrared line-profiling spectrometer installed on Chandrayaan-1. It has an effective wavelength range of 940–2400 nm (256 spectral channels) and maintains high thermal stability. The footprint of SIR-2 is circular with a radius of 100 m. See Mall et al. (2009) for a detailed description of the properties and the calibration of the SIR-2 instrument. In Step 1 of the data-processing procedure, the radiance data are divided by the solar irradiance and corrected by the solar distance. The solar irradiance is a solar spectrum resampled from MODTRAN4 (Gueymard, 2004) at the SIR-2 wavelength. Step 2 involves normalization to a standard geometry (i = 30°, e = 0°, and g = 30°) using a photometric function based on the observation geometry and a spherical lunar topographic model. The photometric function described by Shkuratov et al. (1999) and its parameters are adopted for SIR-2 data. At the end of the data processing, a Savitzky–Golay filter of order 3 that uses a frame size of 11 spectra is applied to the reflectance spectra.

2.5. RObotic Lunar Observatory

The RObotic Lunar Observatory (ROLO) is an Earth-based telescopic system developed to establish the Moon as a radiance source for on-orbit calibration of spacecraft instruments. The spectral range of ROLO observations is 350–2400 nm with 32 spectral channels. The spatial resolution of ROLO is 7.12 × 14.3 km. See Kieffer and Wildey (1996), Stone and Kieffer (2002), and Kieffer and Stone (2005) for detailed descriptions of ROLO properties and calibration.

In Step 1 of the data-processing procedure, the radiance data is divided by the solar irradiance and corrected by the solar distance. The solar irradiance is a solar spectrum resampled from MODTRAN4 (Gueymard, 2004) at ROLO wavelength. Step 2 is normalization to a standard geometry (i = 30°, e = 0°, and g = 30°) using a Lommel–Seeliger limb-darkening photometric correction based on the observation geometry.

2.6. Terrain Camera

The Terrain Camera (TC) is a stereoscopic, monochromatic (spectral sensitivity of 458–752 nm) camera installed on SELENE. It consists of two independent cameras (TC1 and TC2) with slant angles of ±15° from the nadir vector. The swath widths of TC are 35 km (nominal) from SELENE’s nominal 100 km altitude. TC acquires push-broom imaging data. The spatial resolution of TC is 10 m from the nominal altitude. See Haruyama et al. (2008b,c) for a detailed description of TC properties and calibration.

In Step 1 of the data-processing procedure, the radiance data is divided by the solar irradiance and corrected by the solar distance. The solar irradiance is a solar spectrum integrated from Newkirk (Gueymard, 2004) at the TC observation wavelength (from 430 to 850 nm). Step 2 is normalization to a standard geometry (i = 30°, e = 0°, and g = 30°) using the limb-darkening function described by McEwen (1996) with the coefficients for photometric function and the phase function parameters for Clementine 750 nm band (http://www.actgate.com/act/clemcal/alfred.doc) that were used by the US Geological Survey (USGS).

3. Comparison of reflectance spectra of representative geologic settings

3.1. Spectra derived in each data-processing step

Spectra derived for different data-processing steps described in Section 2 are compared for each instrument in Fig. 1. Spectra that result from each data-processing procedure (Table 1) are labeled as M³_step1, M³_step2, and so on. All data in Fig. 1 are spectra of the Apollo 16 standard site, which is used by the Clementine UVVIS camera (Elison et al., 2003) and Earth-based telescopic observations (Pieters, 1999) as an optical standard site. It is 2 × 5 km in size and is located 10 km west of the Apollo 16 landing site in a highland region. All radiance (right axis) spectra are presented in units of W/m²/μm/str, and all reflectance (left axis) spectra are presented in units of radiance factor (RADF). RADF (Hapke, 1993) is defined as the ratio of the bidirectional reflectance of a surface to that of a perfectly diffuse surface illuminated at an incidence angle of zero. For all reflectance data discussed here, geometric conditions are normalized to a standard geometry (i = 30°, e = 0°, and g = 30°). Spatial resolutions of each data are as follows. MI is the whole area of the Apollo 16 standard site (13,500 pixels); SP is seven continuous footprints, observed at the eastern edge of the Apollo 16 standard site; M3 is the whole area of the Apollo 16 standard site (300 pixels); ROLO is 2 × 3 pixel data of the whole area of the Apollo 16 standard site; and SIR-2 is nine continuous footprints, observed in an area 20 km west of the Apollo 16 standard site.

Radiance values obtained by the instruments differ significantly because of differences in observation geometry (i, e, and g) of the measurements, while the reflectance values became more consistent after normalizing to the standard geometry. Differences and improvements in reflectance spectra that result from each data-processing step are observed in each instrument’s data. The ground-truth corrections result in smoother spectra for each area, as observed in laboratory spectra representative of the area (discussed in Section 4).
3.2. Reflectance spectra derived by each instrument

The reflectance spectra of the Apollo 16 standard site derived by the instruments are compared in Fig. 2a. Despite the diversity in observation geometry, spatial resolution, and wavelength resolution, the derived reflectances match well in absolute number and spectral shape except for SP_step3 and SIR2_step2. This result is a good indication of compatibility across datasets. SP_step3 has a much higher reflectance than the other datasets because the data are calculated to reproduce absolute albedo of a “ground-truth” laboratory-measured Apollo soil reflectance (standard 62231), which has a much higher reflectance for the correction as discussed below while other data (MI_step3, SP_step2, M3_step5, and ROLO_step2) use the absolute albedo at 750 nm as observed by each instrument. There is a problem of absolute albedo with correction by matching Apollo 16 standard site remotely-sensed data to Apollo soil reflectance (Hillier et al., 1999). Ohtake et al. (2010) suggested two main sources for the problem: (i) differences in soil composition and/or maturity between the 62231 sampling site and the Apollo 16 standard site and (ii) differences between the compaction states of the laboratory and the actual lunar surface. Details of these effects will be discussed in Section 4. The Step 3 correction is not applied to SP archived data but is presented here for discussion. The lower reflectance in SIR2_step2 is likely to have

Fig. 1. Spectra of the Ap16 standard site derived by each instrument for different data-processing steps. Details of the data-processing steps are discussed in the text. (a) MI. (b) SP. (c) M3 (OP1a). (d) SIR-2. (e) ROLO. The horizontal axis in each panel is adjusted to the observed wavelength of each instrument. Dashed lines indicate 1000 nm wavelength. Differences and improvements in each instrument spectra with data correction are clear in these figures. In (c), M3_step4 and M3_step5 are nearly identical except at the wavelength around 1000 nm where M3_step4 is slightly higher than M3_step5.
several causes as the location of the SIR-2 observation differs slightly from the one covered by the other instruments, the photometric correction differs from those used by the other instruments (see also a companion paper by Besse et al. (2013b)), and possible residual but regular instrumental artifacts. The wavelength range of 0.6–0.8 μm is the part of the spectrum with the most consistent data across instruments with regard to the absolute reflectance. Small differences in slope are observed among instruments. SP has the steepest slope and M3 has the flattest slope, while MI and ROLO have intermediate slopes. The reason for these slope differences is not clear but may be related to spatial resolution differences among these datasets because it is possible that different contributions of small shadows generated by surface roughness in various scales, small and very fresh craters, and fresh boulders cause these differences (effect of different spatial resolutions in the reflectance and the slope will be discussed in Section 5). The remaining error in photometric correction is another possible cause for the slope difference because photometric correction has wavelength dependence as discussed in a companion paper by Besse et al. (2013b, Fig. 6).

Reflectance spectra of a mature mare soil (Serenitatis) are presented in Fig. 2b, and those of a fresh mare region (Messier A) are presented in Fig. 2c (locations and measurement geometry for data acquired at Serenitatis and Messier A are presented in Fig. 3 and listed in Table 5 of a companion paper by Pieters et al. (2013)). Reflectance spectra of the crater Messier A have a stronger absorption band at 1.0 μm than those of Serenitatis. This absorption is weakened by space weathering in the mature soil at Serenitatis. Differences in absolute reflectance values are observed in these two regions, although the spectral shapes are similar. SP and MI have similarly higher reflectances, though the slope of SP is slightly greater than that of MI, while M3 and SIR-2 have lower reflectance. This tendency of M3 and SIR-2, which have a lower reflectance than SP and MI, is observed in the Apollo 16 landing site, but the differences in the mare regions are greater than those at the Apollo 16 landing site. The reason for these differences is not clear but is likely to have several causes including systematic photometric effects described in companion papers by Pieters et al. (2013) and Besse et al. (2013b) (g of each instrument have wide ranges from 23.4° to 69.5° in Serenitatis and from 20.2° to 54.7° in Messier A), possible residual but regular instrumental artifacts, and different spatial resolution (see discussion in Section 5). The effect of M3 adopting photometric function correction of highland regions for all datasets (for delivery to PDS which includes only one photometric correction), even in mare regions is a possible cause of the difference. However, the estimated error for this effect is relatively small since the photometric function differences between highland and mare regions reported by Yokota et al. (2011) in Fig. 11a based on Kaguya SP data are small (less than 2%) in the g range from 20° to 75°.

Fig. 2. Reflectance spectra derived by each instrument. (a) Ap16 standard site (mature highland). (b) Serenitatis (mature mare). (c) Messier A (fresh mare). (d) Reflectance ratios of the Ap16 standard site relative to MI reflectance. MI reflectances were calculated by interpolation between nearest band data to match the wavelength of the compared instruments. Beginning with this figure, each instrument spectrum is indicated by the same color in this paper. The size of the symbol indicates the relative spectral resolution of the data (an instrument with higher spectral resolution has a smaller symbol). Spatial resolutions for each instrument’s data from the Apollo 16 standard site are described in the text. Spatial resolutions for each instrument’s data from Serenitatis and Messier A are as follows. MI: 6 × 6 pixels to match the standard data analysis procedure. SP: 1 footprint. M3: 3 × 3 pixels. ROLO 1 × 1 pixel. SIR-2 1 × 1 pixel. The absolute reflectances and slopes of the spectra may vary among instruments, but the spectral shapes match quite well, indicating the compatibility of the datasets.
Reflectance ratios of different instruments for the Apollo 16 standard site relative to measurements of MI are presented in Fig. 2d. It is very clear that the derived spectral shapes of the instruments match quite well at wavelengths of 0.75–1.55 μm, as demonstrated by the flat lines across this wavelength, though the slopes differ slightly from 0.415 to 0.75 μm. This spectral relationship indicates high compatibility of all instrument datasets, especially at the wavelength of 1 μm, which is very important for estimating and interpreting lunar surface composition using these data.

4. Representative laboratory-measured spectra

Laboratory-measured reflectance spectra of representative lunar material from the RELAB collection are presented in Fig. 3a to illustrate some of the diagnostic spectral properties of the near-infrared bands. The presented materials are mature highland soil (62231), immature highland soil (immature mare soil, mature mare soil, and mare basalt) are presented. Data are from the RELAB database (http://www.planetary.brown.edu/relab/). (b) Laboratory-measured reflectance spectra of 62231 soil (same spectra as in (a)) and corresponding remote-sensing data. The red spectra are MI data of Apollo 16 standard site (ML_Ap16StS) and sampling site of 62231 soil (ML_62231SaS). Light-blue hatching indicates the range of laboratory-measured reflectance for 62231 soil at different densities (density ranges from 0.811 to 0.933 see Ohtake et al., 2010 for details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Spectral reflectance properties of the Moon

The absolute reflectance of the Moon at 1500 nm ranges from 0.08 to 0.3 in most locations, as demonstrated in Fig. 12 of a companion paper by Pieters et al. (2013, Fig. 8). This is why all instruments discussed in this paper derive datasets without matching the absolute reflectance of Apollo 16 standard site observational data to laboratory-measured 62231 soil reflectance.

The mature soils of highland (62231) and mare (12070) have strong absorption band around 1.0 μm because it has the least space weathering.

Laboratory-measured reflectance spectra of 62231 soil and corresponding remote-sensing data are presented in Fig. 3b. In the figure, it is evident that 62231 soil (black line) has a much higher reflectance than the MI data of Apollo 16 standard site (ML_Ap16StS), suggesting a problem in correcting remote-sensing data by matching Apollo 16 standard site observational data to laboratory-measured 62231 soil reflectance. In addition, MI data of 62231 soil sampling site (ML_62231SaS) has higher reflectance than the Apollo 16 standard site, indicating a difference in soil composition and/or maturity between the Apollo 16 standard site and the 62231 soil sampling site. The compaction state of the observed soil causes a reflectance change Hapke, 2008 (example of this change is presented as light-blue hatching in Fig. 3b) large enough to absorb the difference between laboratory-measured 62231 soil and MI_62231SaS. These two effects combined are capable of explaining the error source of previous corrections (as reported by Ohtake et al., 2010). This was tested and confirmed by comparing laboratory-measured and remote-sensing reflectances of other Apollo sampling sites as discussed in a companion paper by Pieters et al. (2013, Fig. 8). This is why all instruments discussed in this paper derive datasets without matching the absolute reflectance of Apollo 16 standard site observational data to laboratory-measured 62231 soil. In spite of the effect of the material compaction state discussed above, it is important to note that the major differences observed in Fig. 3a (absorption band strength, absorption band center wavelength, and continuum slope) are due to composition and maturity.
Spectra with different spatial resolutions can differ even if the data correction for each instrument is perfect because the surface composition and/or compaction status of the observed area may differ at smaller and larger scales. For example, the ring of the Orientale Basin generally indicates a very plagioclase-rich composition (Ohtake et al., 2009; Pieters et al., 2009b) with a diagnostic crystalline plagioclase absorption band around 1.25 μm. However, other areas of the ring exhibit a weaker absorption band around 1.25 μm and may have lower reflectance than the crystalline plagioclase-rich material. In some cases, this is associated with differences in spatial resolution of the measurements. Reflectance spectra acquired by MI, SP, and M3 of an area along the Orientale Inner Rook mountains are presented in Fig. 4b. MI spectra with three different spatial resolutions (averaged in different pixels) are denoted by red symbols. These spectra correspond to nominal MI resolution for data analyses (120 × 120 m/pixel, which corresponds to 6 × 6 pixels), SP resolution (500 × 500 m/pixel), and telescopic resolution (10 × 10 km/pixel). MI spectra with 1 × 1 pixel and 6 × 6 pixel averaging are usually similar except at very steeply sloped or rough surface locations. However, 6 × 6 pixel averaged spectra in the nominal case are used for data analyses in this study to minimize possible errors caused by surface roughness and to detect the geologic context with certain size. All spectra that exhibit the 1.25 μm crystalline plagioclase feature have an effective spatial resolution that allows measurement of material within the 4 km bright crater, but this feature is lost at lower resolution when much of the surrounding material in included as well. In addition to the absorption feature, absolute reflectance decreases (Fig. 4b) but the spectral slope increases (Fig. 4c) as the MI observation size increases (from higher to lower spatial resolution) possibly because of different contributions of small shadows generated by surface roughness on various scales, small and very fresh craters, and fresh boulders. This trend of slope change is also observed when MI and SP data are compared, though the absolute change in slope differs between them. Comparison of reflectance spectra of the same area but with different spatial resolutions (Fig. 4) and surface morphologies (rugged steep-slope vs. smooth terrain) illustrates the importance of spatial resolution in detecting diagnostic features, and consequently in geologic interpretation. With lower spatial resolution data, spatial contamination can easily obscure the presence of diagnostic mineral absorption through dilution and masking by surrounding material.

A rock surface and a regolith surface of the same composition can exhibit similar wavelength centers of absorption bands but have different overall reflectance and absorption depths. This phenomenon can arise from differences in the average path length of radiation transmitted through the material and differences in their space weathering degree before being scattered and measured by the instrument due to the physical properties of the target. Similarly, the abundance and distribution of particle sizes in a mixture can affect band strength. Therefore, a mixture of rocks and soil on the lunar surface, as well as the spatial extent of a given unit, definitely affects the measured reflectance spectra, which is important to consider when interpreting the high-resolution image data currently available. In general, it is useful to have image data of ×10

Fig. 4. Spectra of an area along the Orientale Inner Rook ring acquired by MI, SP, and M3 with different spatial resolutions. (a) Geologic Context. Red boxes indicate areas of MI data averaged with different spatial resolutions, as presented in figure (b) (120 × 120 m/pixel, 500 × 500 m/pixel comparable to SP, and 10 × 10 km/pixel comparable to telescopic data). The blue box indicates the location of the M3 spectra. Comparison of spectra (b) and scaled spectra (c) with different spatial resolutions. The red spectra were all derived by averaging MI data with different spatial resolutions. Low spatial resolution can obscure a plagioclase absorption band, as observed in the 10 × 10 km/pixel MI spectra. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
spatial resolution to provide geologic context for the mineralogical interpretations of high spectral resolution reflectance data.

6. Combined reflectance data for the Bullialdus area

This section presents the results of combined (and in some cases compared) analyses using all datasets (M3/SP/MI/SIR-2/TC data) for Bullialdus crater (−20.7°N, 337.8°E; 60 km in diameter) to demonstrate the efficiency of such analyses. Footprint locations of the available datasets for each instrument are indicated in Fig. 5a, overlaid on an MI base map. Red dots denote the SP footprints, blue hatches represent the M3 imaged areas, and light blue dots represent the SIR-2 footprints. TC observations covered the entire area. Fig. 5a demonstrates the wealth of data available and the diversity of multiple coverage of the combined instrument
Bullialdus crater is located in the Nubium basin and is surrounded by mare material (orange in upper left Fig. 5b and light blue in Fig. 5c). Fig. 5b is a color-composite image of Bullialdus crater from the M² data (M3_step5). Band assignments are integrated band depth at 1 μm (red), integrated band depth at 2 μm (green), and 1.5 μm albedo (blue). The apparent compositional heterogeneity of the central peak is clear in the variations from red to green and cyan, indicating a variable abundance of mafic minerals, as suggested previously by Pieters (1991). Fig. 5c is a color-composite image of the same region from the MI data (MI_step3). Red denotes the continuum-removed absorption depth of 0.95 μm, green denotes that of 1.05 μm, and blue denotes that of 1.25 μm. Compositional heterogeneity of the central peak is observed in the MI and M² data, as well as distinct compositional contrast in the crater’s terraced wall and floor.

A close-up image of the central part of the central peak (white box in Fig. 5c) is presented in Fig. 5d as a TC image (without photometric correction), in Fig. 5e as an MI 750 nm-band image after photometric correction using local topographic information, and in Fig. 5f as an MI color-composite image. Spectra of the central peaks for areas indicated in Fig. 5f are compared in Fig. 6, and spectra of the terraced wall (black box in Fig. 5c) are compared in Fig. 7. The high-resolution TC image (Fig. 5d) of the area exhibits local regions of blocks, but suggests a relatively smooth surface in this area with patchy variations in reflectance but no apparent sharp morphologic boundary. Comparison of Fig. 5e and f indicates that the two distinct observed units (blue and orange in the 5f color-composite) differ dramatically in spectral properties (and hence composition), whereas there are no prominent differences in reflectance (gray shade in Fig. 5e is not caused by the topographic effect because this image was corrected to compensate for that effect). The orange lithology has higher-reflectance spots and areas in some locations, but the reflectances of blue and orange lithologies are similar in most areas. This suggests that spectral differences between blue and orange units are not caused by a difference in the degree of space weathering but rather by differences in some other parameter(s), likely including composition and/or impact-related component, indicating that these two units represent different lithologies. These two lithologies are interlaced (Fig. 5f), at least in some locations, rather than having a simple boundary.

Reflectance spectra and continuum-removed spectra for several locations representative of the area are presented in Fig. 6a and b as MI spectra, in Fig. 6c and d as SP spectra, and in Fig. 6e and f as M² spectra. A continuum was removed to enable us to compare relative absorption band strength and absorption band wavelength more clearly among observed spectra. A continuum was defined as a line connecting the reflectance values in the normal reflectance scale between two wavelengths selected. Nearest data points to 750 nm and 1550 nm were selected (and fixed) as an approximation of the contact points for all the analyzed spectra here to obtain compatibility among the spectra. The continuum is removed from the reflectance by dividing each reflectance spectrum by its continuum. The selected contact points may not be best suited for all the spectra, therefore continuum-removed spectra exceeded 1 in some cases. Also, because we used a straight line as the continuum, even if the wavelengths selections are best we can still have spectra exceeded 1 because of the nature of the spectra and the straight line.

Note that the absolute reflectances of the two lithologies appear to differ in Fig. 6 because we selected the higher-reflectance spots of the orange unit for comparison in order to see the clearest spectra. The locations of the data points are indicated in Fig. 5f as white dots labeled from CP_1 to CP_8. It is difficult to compare the reflectance spectra for the same spots in MI/M²/SP because the limited availability of the best representative spectra in this region for each instrument results in an absolute reflectance difference (Fig. 6a, c, and e). However, the spectra from these three instruments indicate consistent compositional properties of the two units. The blue unit in Fig. 5f, which corresponds to CP_1, CP_5, and CP_7 (blue spectra in Fig. 6), exhibits a notably weak absorption band around 0.9 μm for all instruments. However, the orange unit in Fig. 5f, which corresponds to CP_2, CP_6, and CP_8 (orange spectra in Fig. 6), has a well-developed and clear absorption band at the same wavelength of around 0.9 μm. Though the spectra from the orange unit have a clear absorption band around 0.9 μm, composition of the lithology possibly is feldspathic judging from that the absorption band depth is not extremely strong. The similarity of spectra for the two lithologies that exhibit absorption maxima at the same wavelength suggests that the spectral difference between the two is not caused by a difference in mafic silicate composition. Instead, the differences could be due to (i) the difference in modal abundance of the mafic silicate, (ii) the presence of an impact-related component (melted or shocked glass) in the blue lithology, or (iii) the difference in compaction state and particle size. If case (i) is true, and if both lithologies have the same physical characteristics (e.g., grain size and glass/crystalline component), the two lithologies could be consistent with an anorthositic norite and an anorthosite in contact with one another, although a lower mafic content to explain the weaker absorption band around 0.9 μm in the blue unit would imply higher reflectance than is observed. A different interpretation based on case (ii) may require more complex interlaced texture of the two lithologies than observed. A difference in grain size is not likely to cause the spectral difference because smaller grain sizes with a weaker absorption band tend to have higher reflectances, which is opposite to what is observed in this region. The two lithologies (anorthosite) are not the purest anorthosite (PAN) (as defined by Ohtake et al., 2009) possibly due to Bullialdus being located within the Nubium basin (mare region) and its central peak being uplifted deep crustal material or intrusive rocks.

Table 2

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* Source files are TCO.MAP.02.S21E336S23E340S.img and TCO.MAP.02.S18E336S21E339S.img.
instruments’ spectra are consistent in spectral shape, indicating a slightly longer absorption center wavelength than the central peak orange lithology, which corresponds to the slightly different mafic silicate composition of this area compared to that found in the central peaks (i.e., the presence of more Fe- and Ca-rich pyroxenes). The absolute reflectance of MI and SP and that of M3 and SIR-2 are consistent, although slightly different between the two groups. This difference is possibly due to the complex mixture of different photometric correction and characteristics of each instrument, as discussed in the previous section. Detailed analyses of these combined datasets can be used to evaluate such compositional variation across the crater interior and reveal their origin.

In summary, this paper reports our comparison and some combinations of multiple lunar datasets from different data sources. It

Fig. 6. Comparison of reflectance spectra from the center of the Bullialdus central peak (areas in Fig. 5f). (a) MI reflectance spectra. (b) MI continuum-removed spectra. (c) SP reflectance spectra. (d) SP continuum-removed spectra. (e) M3 reflectance spectra. (f) M3 continuum-removed spectra. Blue and orange spectra indicate spectra of the same lithologies, though the locations of the spectra are not exactly the same. In spite of the significant difference in band strength between the two lithologies sampled by the blue and orange spectra, their absorption center wavelengths are similar, suggesting compositional similarity of the mafic silicate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
has clearly demonstrated that combining high-spatial-resolution re-reflectance, color-composite images, and hyper-spectral data ob-tained by different missions and different instruments enables complex geologic environments to be explored in ways not possible before. This capability provides a powerful tool for understanding the composition and geology of the lunar surface and for planning the next steps of exploration.

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