Lunar Mineralogical Spectrometer on Chang’E-5 Mission

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Abstract

The Lunar Mineralogical Spectrometer (LMS) is one of the main payloads on the Chang’E-5 (CE-5) lunar probe, belonging to the China Lunar Exploration Program. The scientific objective of the LMS is to explore the mineralogical composition and search for evidence of -OH/H2O in the sampling area. The LMS consists of an optomechanism unit, a dustproof calibration unit (DPCU) and an electronic unit. The LMS is installed on the lander about 1.4-m above the lunar surface, the field of view (FOV) is 4.17° × 4.17°, the instant FOV of the visible imaging channel is 0.28 mrad, and the typical spatial resolution is 0.56 mm/pixel @ 2 m distance. The rotation range of the 2D scanner is ±22.5° along the azimuth axis and 0 ∼ 30° along the elevation axis, making it possible to observe the sampling area or to select important observing targets. The dispersing beam uses acousto-optic tunable filters, and target detection is performed with a 2D scanner. The LMS acquires spectral imaging information covering 480–950 nm, and reflectance spectra of 900–3,200-nm, both at a 5-nm/band sampling interval. The spectral resolution is 2.4 ∼ 9.4 nm in the visible and near-infrared channels and 7.6 ∼ 24.9 nm in the short–medium-wave infrared channel. The LMS has a 588-band detection capability designed for fine spectral observation of sampling points and wields a 20-band full-view multi-spectral mode to observe candidate areas prior to sampling. The DPCU of the LMS is integrated with a calibration diffuser that is used for in-flight calibration on the lunar surface using solar irradiation, thus improving the quantitative level of scientific data.

Keywords Lunar Mineralogical Spectrometer · LMS · AOTF · In-situ · Performance

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Abbreviations

Al-SiC  Aluminum Based Silicon Carbide
AOTF  Acousto-Optic Tunable Filter
CE  Chang'E
CMOS  Complementary Metal-Oxide-Semiconductor
DPCU  DustProof Calibration Unit
DN  Digital Number
EM  Engineering Model
EU  Electronics Unit
FM  Flight Model
FOV  Field of View
FPGA  Field Programmable Gate Array
FWHM  Full Width at Half Maximum
IFOV  Instantaneous Field of View
InGaAs  Indium Gallium Arsenide
IR  Infrared
ISEM  Infrared Spectrometer for ExoMars
LIS  lunar infrared spectrometer
LMS  Lunar Mineralogical Spectrometer
LUT  Look-Up-Table
LAC  lander–ascender combination
MCT  Mercury Cadmium Telluride
MLI  Multi-Layer Insulation
MTF  Modular Transfer Function
MWIR  Medium-Wave Infrared
NIR  Near infrared
NIM  National Institute of Metrology
OMU  Optical Mechanical Unit
PI  Principal Investigator
REFF  REFlectance Factor
RMS  Root Mean Square
RMSE  Root Mean Square Error
SITP  Shanghai Institute of Technical Physics
SWIR  Short Wave Infrared
S/N  Signal-to-noise ratio
TEC  Thermal-Electric Cooler
TCA  Thermal Control Accessory
V-NIR  Visible and Near-Infrared
VNIS  Visible and Near-infrared Imaging Spectrometer

1 Introduction

As the nearest celestial body to the Earth, the Moon is critical to our ability to develop deep-space exploration capabilities. There are three main methods of lunar exploration: orbital remote sensing, in situ observation, and sampling returns (Li et al. 2019b). The Moon Mineralogy Mapper (M3) instrument onboard the Chandrayaan-1 lunar probe is a typical orbital remote-sensing payload (Pieters et al. 2009; Green et al. 2011). The data provided by the M3
has formed the current baseline for lunar composition studies (Li et al. 2018; Li and Milliken 2016). In particular, it confirmed the presence of OH/H₂O on the surface of the moon (Pieters et al. 2009b; Li and Milliken 2017). China’s Chang ’ E-3 (CE-3) and Chang ’ E-4 (CE-4) probes provide typical in situ scientific exploration on the lunar surface. The visible and near-infrared imaging spectrometer (VNIS) onboard the CE-3 (He et al. 2014b,a) is the world’s first in situ spectral observation instrument on the lunar surface (Ling et al. 2015). The VNIS onboard CE-4 (Li et al. 2019d; He et al. 2019) performed the first in situ spectral detection on the far side of the Moon (Li et al. 2019a). The CE-4 rover (Yutu-2) has been exploring the Von Kármán crater for over two years, and the VNIS data shows that the rover observation area has been relatively uniform, consisting of pyroxene, plagioclase, molten cement, and a small amount of olivine. The mineral absorptions of the olivine-norite in the observation area are robust, offering quite reliable analyses opportunities of mineral composition (Lin et al. 2019). High-albedo fragments have also been observed randomly distributed in craters along the path of the CE-4 rover. These fragments were analyzed to have been molten glass created by impact forces, giving us the first in situ detection of pure glass on the Moon (Lin et al. 2020).

The Chang ’ E-5 (CE-5) probe was successfully launched onboard the Long March 5 carrier rocket from the Wenchang Satellite Launch Center on November 24th, 2020. The lander–ascender combination (LAC) arrived at Mons Rümker in the northern part of Oceanus Procellarum (Liu et al. 2021; Qian et al. 2020). After a period of in situ scientific exploration, the ascender took off from the lunar surface on December 3rd, 2020, realizing China’s first unmanned sampling return. This success has congealed the Chinese lunar exploration trilogy ideology of “orbiting, landing, and returning” (Ye and Peng 2006).

Upgraded from the CE-3 and CE-4 VNIS systems based on acousto-optic tunable filter (AOTF) (Korablev et al. 2018), the current lunar mineralogical spectrometer (LMS) (He et al. 2019) is one of the main payloads on CE-5 LAC, whose scientific mission is to detect mineral composition and find -OH/H₂O in the sampling area. By acquiring spectral data of targets in the sampling area, mineral composition and distribution analysis can be accomplished to provide scientific data for further investigation of the material composition of lunar resources. It also helps with Earth-based laboratory sampling studies.

Spectrometers dispersed by AOTF are well suited for deep space landing and roving missions, and only VNIS on CE-3/4 and LMS on CE-5 have achieved in-situ lunar exploration. Other deep space applications are Perseverance, ExoMars, Luna-Glob Luna-Resurs, Phobos-Grunt and Hayabusa2-MASCOT. The SuperCam of the Perseverance (Wiens et al. 2021; Fouchet et al. 2021; Perez et al. 2017), launched in 2020, contains an AOTF-based short-wave infrared spectrometer, enabling 1.3-2.6 µm spectral detection on Martian surface. ExoMars contains Infrared Spectrometer for ExoMars (ISEM) and MicrOmega: the ISEM (Korablev et al. 2017, 2014; Yury et al. 2019) can realize 1.1-3.3 µm spectral measurements by AOTF dispersion, and the MicrOmega (Bibring et al. 2017b) can provide 0.99-3.65 µm fine microscopic spectral imaging of the Martian samples. The lunar infrared spectrometer (LIS) (Korablev et al. 2014), mounted on the Luna 25/27 robotic arm, onboard the Luna-Glob and Luna-Resurs missions, has a similar design to the ISEM. The MicrOmega has three versions, besides onboard ExoMars, it is also designed onboard Phobos-Grunt (Bibring 2011) and Hayabusa2-MASCOT (Bibring et al. 2017a), as the performances have improved with each generation. In general, with similar specifications of spectral range and resolution, differentiated designs were carried out for mission realization. Based on the stationary platform characteristics, the LMS has the capacity of large field of view scanning imaging, and staring detection to collect spectral images in the visible band and spectra in infrared bands. In particular, the LMS is able to adapt to the high temperature of the moon midday with high spectral resolution and signal-to-noise ratio (S/N).
This paper introduces the design, operation, and performance of the LMS in detail. First, an instrument overview and mission analysis is presented, followed by that of the instrument design. Laboratory calibration and performance is then discussed, and in-flight operations are described.

2 Instrument Overview

The LMS inherits the design concepts of the CE-3 and CE-4 rovers’ VNIS systems. Dispersed by AOTFs (Korablev et al. 2018), the LMS detects the reflection and thermal radiation spectra of the lunar surface. For a given acoustic-signal radio frequency (RF), the quasi-monochromatic wavelength is diffracted by the AOTF (Strojnik Scholl et al. 2015; Bibring et al. 2017a; Belyaev et al. 2017). For the visible-to-near-infrared (V-NIR) channel (0.48–0.95 µm), diffracted light is converged onto an area array detector to form a spectral image cube of the lunar surface. In the infrared channel (0.9–3.2 µm), diffracted light is detected by the unit detector to obtain the spectral information of the target. The LMS is equipped with the static LAC of the CE-5, and, with the help of a 2D scanner, different areas can be observed, acquiring spectral information of the sampling area.

The LMS is installed on the inner side of the +Z-Y panel of the CE-5 LAC and is thermally insulated. A dustproof mechanism and the 2D scanner of LMS protrude out of the LAC through a window opening, as shown in Fig. 1.

The design scheme of the LMS is shown in Fig. 2, including an optical mechanical unit (OMU), a dustproof calibration unit (DPCU), an electronics unit (EU), and more.

The main characteristics of the LMS are listed in Table 1. To meet the scientific exploration mission, the LMS has the following main functions (He et al. 2019): high-resolution 480–3,200-nm reflectance spectral observation of the lunar surface capable of obtaining spectral images of 480–950 nm; 2D scanning of an observation target that can be changed according to demand; and dustproof in-flight calibration.

Based on the functional composition, the LMS has three in-flight operation modes that can acquire spectral information from the observation target:

- Unlock: unlock the DPCU and enable lunar observation.
Table 1 Main characteristics of the LMS instrument onboard CE-5 (He et al. 2019)

| Parameters                  | Specifications                                      |
|-----------------------------|-----------------------------------------------------|
| Spectral range (nm)         | 480-3200                                            |
| Spectral resolution (nm)    | 2.4-24.9                                            |
| Field of view (°)           | 4.17 × 4.17                                         |
| Quantization (bit)          | 10 @ VIS; 16 @ infrared                             |
| Data volume                 | 15MB for full-band observation and in-flight calibration mode (without compression) |
| Signal-to-noise ratio       | ≥50 (peak ≥ 500)                                    |
| Modular transfer function   | ≥ 0.14                                              |
| Scanning precision (°)      | ≤ 0.17                                              |
| Mass (kg)                   | ≤ 5.57, exclude 0.12 kg of Thermal Control Accessory (TCA) |
| Overall dimension (mm)      | 286.5 * 260 * 225                                   |
| Power consumption (W)       | 15.17                                               |
| Operating temperature (°C)  | -20 ~ +70                                           |

- Full-band observation of the target, which includes adjusting the 2D scanner to point at the target to acquire V-NIR spectral images and infrared spectral data at a sampling interval of 5 nm/band for 588 bands total.
- Full-view scanning and multi-spectral observation, which includes adjusting the staring field of view (FOV) according to the look-up-table (LUT) of the pointing angle in sequence and acquiring multi-spectral visible images and infrared data during each view. The number of scanning FOV is 180, with six bands in the visible (VIS) channel, six in the near infrared (NIR), four in the shortwave infrared (SWIR) channel, and four in the medium-wave infrared (MWIR) channel, as shown in Table 2.
Table 2  Detailed information of full-view scanning and multi-spectral observation of LMS

| Channel | Band number | Wavelength (nm) |
|---------|-------------|-----------------|
| VIS     | 6 (imaging) | 485, 560, 640, 750, 850, 900 |
| NIR     | 6 (spectra) | 950, 1000, 1050, 1100, 1250, 1450 |
| SWIR    | 4 (spectra) | 1550, 1800, 2000, 2200 |
| MWIR    | 4 (spectra) | 2600, 2800, 3000, 3200 |

In-flight calibration, which includes adjusting the 2D scanner to point at the calibration diffuser inside the DPCU to acquire spectral data in the solar illumination.

According to flight conditions, the DPCU of the LMS is unlocked 6 h after landing, and full-view multi-spectral detection is carried out to observe the sampling area prior collecting samples with the robotic arm. When sampling begins, full-spectral observation is carried out by targeting an area of interest, including the same point before and after sampling. On the Moon, the installation height of the LMS is approximately 1.4 m. Using a mapping process, the matching relationship between the full FOV coverage area and the sampling area of the robotic arm is shown in Fig. 3, and six of the twelve samplings were actually done in the common area.

3 Instrument Design

The LMS comprises an OMU, a DPCU, and an EU, as shown in Fig. 4. The OMU includes a 2D scanner, fore-optics, V-NIR sub-modules, and short–medium-wave infrared (S-MWIR) sub-modules. The 2D scanner comprises azimuth- and elevation-axis systems, including a scanning mirror, a U-shaped frame, an ultrasonic motor, a harmonic reducer, and a potentiometer. The solar reflection beam of the observation target enters the V-NIR sub-module and S-MWIR module through the fore-optics to form spectral images and signals. The DPCU was designed integrally with a calibration (Al and Au-coated) diffuser embedded on the DPCU. Combined with the azimuth rotation and a self-locking 2D scanner, the DCPU locks once before launch and unlock once after landing on the Moon. The EU consists of a complementary metal-oxide-semiconductor (CMOS) plane-array detector, three
infrared unit-detectors, signal processing circuits, a field-programmable gate-array (FPGA) main control circuits, and motor-drive circuits.

### 3.1 OMU

The OMU includes a 2D scanner, fore-optics, a V-NIR sub-module, and an S-MWIR sub-module.

As shown in Fig. 5, the multiple spectral channels of the OMU share a mirror with the 2D scanner to realize changes of view. The light signal from the Moon surface is reflected by scanning and folding mirrors. It then enters the internal optical system where it is divided into two beams via aperture division. The beams then separately enter the V-NIR and S-MWIR sub-modules. Both sub-modules use an AOTF for dispersion.

The V-NIR AOTF (LSGDN-5Z) and the S-MWIR AOTF (LSGDN-6Z) of the LMS were developed and manufactured by No.26 Research Institutes of China Electronics Technology
Table 3 Main characteristics of AOTFs in LMS (He et al. 2019)

| Parameters                        | V-NIR AOTF                  | S-MWIR AOTF                |
|-----------------------------------|-----------------------------|----------------------------|
| Material                          | TeO₂                        |                            |
| Spectral range (nm)               | 480–1,450                   | 1,400–3,200                |
| Full-width at half maximum        | 2.6–9.4 nm@<780 nm          | 7.6–20.8 nm@1,400–2,300 nm |
|                                   | 2.4–9.0 nm@>780 nm          | 11.6–24.9 nm@2,200–3,200 nm|
| RF frequency (MHz)                | 45.2–163.6                  | 27.7–66.2                  |
| Angular aperture (°)              | >7                          | >3                         |
| Diffraction angle (°)             | >5.9                        | >6.5                       |
| Power (W)                         | ~2                          |                            |

Fig. 6 FOV relationship of four channels in LMS with observation distance of 2.5 m

Group Corporation (CETC-26). In order to meet the requirements of a wide spectral range, a dual-channel using high-and-low frequency division is adopted. The spectral range of the V-NIR AOTF is 0.48–1.45 μm, and the corresponding spectral resolution is 2.4–9.4 nm. The spectral range of the S-MWIR AOTF is 1.4–3.2 μm, and the spectral resolution is 7.6–24.9 nm. The main characteristics of the AOTFs are listed in Table 3.

The designed observation distance of the LMS is 1–5 m, and the actual installation reference distance is 2.5 m. A dual-channel FOV is guaranteed by the size of the field stop. The NIR spectrometer and the VIS imaging spectrometer share the field stop, whose central FOV overlaps. The SWIR and MWIR spectrometer share the field stop. The relationship of the dual-channel FOV is guaranteed via optical adjustments. The incident aperture of the dual-channel optical system is 12-mm apart. Calculated at a 2.5-m object distance, the deviation of the dual-channel FOV is 16.6 pixels with the V-NIR imaging spectrometer. The relationship between the FOV is shown in Fig. 6.

The V-NIR sub-module includes visible imaging and NIR spectrometers, both sharing fore-optics and a V-NIR AOTF. The light is separated from the same diffraction order of the AOTF through a dichroic plate. Part of the light arrives at the CMOS array detector to obtain a spectral image of 480–950 nm. Another part arrives at the near-infrared unit detector to acquire spectra of 900–1,450 nm. The S-MWIR sub-module includes SWIR and MWIR spectrometers, which also share fore-optics and an S-MWIR AOTF. The positive first-order diffraction light of the S-MWIR AOTF converges and arrives at the SWIR unit detector to acquire spectra of 1,400–2,300 nm (Li et al. 2019c). The negative first-order diffraction light arrives at the MWIR unit detector after being converged to acquire spectra of 2,200–3,200 nm.

The optical design parameters of the visible imaging spectrometer and the NIR / SWIR / MWIR spectrometer in the LMS are listed in Table 4. The spectral range of the visible
Table 4  Optical parameters of the LMS

| Parameters                      | VIS                  | NIR                  | SWIR                 | MWIR                |
|--------------------------------|----------------------|----------------------|----------------------|---------------------|
| Spectral range (nm)            | 480–950              | 900–1,450            | 1,400–2,300          | 2,200–3,200         |
| Equivalent focal length (mm)   | Shared fore-optics and AOTF. Fore-optic f=24, collimator f=36 f=86.4 | Shared fore-optics and AOTF. Fore-optic f=24, collimator f=36 f=13.5 | f=13.5 | f=13.5 |
| FOV (°)                        | 4.17 × 4.17          |                      |                      |                     |
| Equivalent F#                  | 10.8                 | 1.6                  | 1.6                  | 1.6                 |
| OTF                            | >0.6@ 20 lp/mm        | –                    | –                    | –                   |

Detectors

| Type                           | CMOS (STAR250)       | InGaAs              | InGaAs              | MCT                 |
|--------------------------------|----------------------|---------------------|---------------------|---------------------|
| Active spectral range (nm)     | 200–1,000            | 750–1,700           | 1,100–2,600         | 2,200–3,600         |
| Pixel Size                     | 25 µm × 25 µm        | 1 mm × 1 mm         |                     |                     |
| Active pixels                  | 512×512              | 1                   |                     |                     |
| Instantaneous noise            | 76e-5, depending on kTC | –                   | –                   | –                   |
| Dynamic Noise                  | 74 dB, (5,000:1) at the analog output | – | – | – |
| Dark Current                   | 4,750e−3/s at RT     | –                   | –                   | –                   |
| Peak D* at 1 KHz (cmHz1/2/W)   | –                   | 9.9E+13             | 8.4E+11             | 6.0E+11             |
| Peak Responsivity (A/W)        | 0.9                  | 1.2                 | 0.8                 |                     |

Table 5  Measured MTF in LMS

| Object distance (mm) | 1500 | 2500 | 3000 |
|----------------------|------|------|------|
| Central FOV MTF of representative wavelength | 0.15 @ 1.2-mm slit pair @ 800 nm | 0.23 @ 1.0-mm slit pair @ 800 nm | 0.22 @ 1.0-mm slit pair @ 800 nm |

The imaging spectrometer is 480–950 nm, and the modulation transfer function (MTF) of the optical system is greater than 0.6@20 lp/mm (Nyquist sampling frequency). The root-mean square (RMS) radius of the diffuse spot in the full FOV is less than half a pixel size, and the RMS radius of the diffuse spot in the NIR/SWIR/MWIR spectrometers is less than that.

The VIS plane detectors are Cypress’s CMOS devices (STAR250) having spectral ranges of 200–1,000 nm and pixel sizes of 25 µm × 25 µm. The pixel number of the CMOS is 512×512, and we only use 256×256 parts in the center. The NIR, SWIR, and MWIR unit detectors were developed by the Shanghai Institute of Technical Physics (SITP) of the Chinese Academy of Sciences independently using Thermal-Electric Cooler (TEC) secondary refrigeration. The spectral ranges are 750–1,700, 1,100–2,600, and 2,200–3,400 nm, respectively. The main characteristics of the detectors used in the LMS are listed in Tables 4.

The MTF of the LMS at different distances was measured and is listed in Table 5.

The 2D scanner is driven by an ultrasonic motor, as shown in Fig. 7, which is similar to the calibration dustproof components of the CE-4 VNIS. The mechanism includes azimuth-
Fig. 7 2D scanner of LMS. (1 – ultrasonic motor of azimuth axis, 2 – harmonic gear drive, 3 – angular transducer in azimuth axis, 4 – angular transducer in elevation axis, 5 – tenon, 6 – scanning mirror, 7 – ultrasonic motor of elevation axis, 8 – U-shape frame)

and elevation-axis systems. The azimuth-axis system includes an azimuth ultrasonic motor, a harmonic reducer, a potentiometer, an azimuth axis, etc. The elevation-axis system includes a elevation ultrasonic motor, a U-shaped frame, a scanning mirror, a potentiometer, an elevation axis, etc. Solid lubrication is adopted in all bearings. The azimuth pointing angle range is \[ \pm 22.5^\circ \], and the elevation range is 0–30\(^\circ\). Potentiometers are used for absolute angle measurement for both azimuth and elevation axes. The quantization angle is 12-bit, and the pointing accuracy is better than \[ \pm 0.17^\circ \].

### 3.2 DPCU

Because the LMS equipment is installed both inside and outside the lander-ascender combination, it is necessary that it be dustproof, sun-shaded, and heat-insulated to the outside. It is equipped with a dust cover and a dust plate that can be deployed using a torsion spring. The integrated design uses the rotation and scanning capabilities of the 2D scanner. The calibration diffuser and latch are embedded on the dustproof plate, and a Ti-alloy tenon is designed for the U-shaped frame of the 2D-scanner azimuth axis, as shown in Fig. 8. Prior to launch, the dust cover is closed, and the U-shaped frame is rotated to a horizontal state with the tenon closed with the dust-plate latch. The dust cover is locked using the locking torque of the ultrasonic motor and harmonic reducer of the azimuth shafting system. After landing on the Moon, the azimuth axis system rotates 15\(^\circ\) counterclockwise, and the latch is separated from the tenon. The dustproof plate is rotated to the unfolded position via gravity and the torsion spring. Thus, the lock of the dustproof device in its launch state and the one-time unlock on the lunar surface is realized.

When the dustproof plate is unfolded, the angle between the optical surface of the calibration diffuser and the installation surface of the LMS is 110\(^\circ\). By adjusting the scanning angle, the LMS observes the self-made Al-based diffuser in the visible band and observes the Au-plated diffuser in the infrared band to finish in-flight radiation calibration with sunlight. The Au-plated diffuser is a customized LabSphere InfraGold diffuser (Green et al. 2011). The hemispherical reflectance (Fig. 10), emissivity, and bidirectional reflectance function test data for the diffusers were obtained, traceable to the National Institute of Metrology (NIM). The mechanism design and the principle scheme of in-flight calibration on the lunar surface are shown in Fig. 9.

### 3.3 EU

The LMS EU comprises eight circuit boards (i.e., a large bottom plate, a main control board, a 2D scanning motor-control board, a visible spectrum signal-processing board, an infrared
Fig. 8  Dustproof mechanism and latching of LMS

Fig. 9  In-flight calibration unit of LMS

The electronics functions of the LMS include receiving the secondary power provided by the payload data processor and providing the required voltage for the electronics of the instrument; communicating with the payload data processor through the RS422 interface and sending scientific data via the LVDS bus; driving the 2D scanner to observe a specific area; driving two AOTFs to diffract light into a specific wavelength; and driving four detectors to acquire spectral information and to perform basic data processing.

A phase-locked amplification method is introduced to eliminate the influence of the AOTF’s zero-order diffraction beam and circuit noise of the quasi-monochromatic light (Li et al. 2019c). The detailed process is shown in Fig. 12. Specific ultrasonic waves are applied to the AOTF crystal to diffract the desired wavelength of the outgoing first-order diffraction light, and it is modulated by switching it on and off. However, the zero-order diffraction light is not modulated. In this case, alternating quasi-monochromatic lights are received by the detectors and are converted to an alternating current, whereas the zero-order diffraction light
is converted to the direct portion of the current. Via current–voltage conversion, narrow-band filtering, in- and reverse-phase amplification, phase-locking, and low-pass filtering, direct-current (DC) signals, the characteristics of the intensity of quasi-monochromatic light are finally output. This process not only eliminates the DC bias caused by the zero-order diffraction light, but it also eliminates the unmodulated circuit noise, effectively improving the S/N of the LMS. The S/N is >100 in the infrared band.

### 3.4 Thermal Control

The LMS endures launching, Earth–Moon transfer, near-Moon maneuvers, orbiting, landing descent, and lunar-surface working-mission phases. The LMS is shut down and its dustproof mechanism is closed prior to launch. When landed, the dustproof mechanism opens, and the LMS is engaged with work. The LMS adopts passive thermal control methods to maintain its working temperature. Insulated installation is introduced between the hood and the LMS.
The OMU, scanning, and dustproof mechanisms are heat insulated. A 15-unit multi-layer insulation (MLI) composed of a F46 Ag secondary surface mirror is coated on the outside part of the LMS to reduce heat exchange between the LMS and cold space, solar radiation, and lunar-surface reflection. A five-unit MLI composed of double-sided aluminized polyester film is coated on the interior of the LMS to reduce heat exchange between the LMS and cold space. The outer part of the LMS is fully coated with a 15-unit F46 Ag secondary surface mirror to reduce heat exchange between the LMS and cold space. The inner part of the LMS, except for the top cover plate, is coated with a five-unit MLI made of double-sided aluminized polyester film to reduce thermal radiation during working periods. The inside and outside surfaces of the LMS top cover plate are sprayed with black paint to enhance the thermal coupling between the LMS and the lander container and to further dissipate heat. During periods on the lunar surface, the LMS work phase begins with lunar sampling. When the dustproof mechanism is opened, the OMU is affected by solar radiation and lunar surface reflection, so the temperature of it gradually increases. To preserve a high S/N on the lunar surface at high temperatures, a TEC refrigeration piece is adopted in the CMOS detection array and infrared detectors, installed directly on the back of the detector through the window reserved on the circuit board after welding, as shown in Fig. 13. The TEC pieces of the infrared detectors are encapsulated inside the detector.

By thermal analyses and balance tests, mission specifications were calculated. Assuming that the time of landing is lunar midday, the temperature of the LMS optical frame gradually rises during a 48-h mission, owing to the influence of heat flow. In this case, when the LMS unlocks the dustproof mechanism after drilling is finished, the temperature of the optical frame could be 36.8 °C. After full-view observation and before robotic-arm sampling, the temperature rises to 45 °C. The LMS performs observations every 2 h during robotic arm
sampling. Hence, after four observations (12 h after landing on the Moon), the temperature of the optical frame could reach +65 °C. If, when robotic-arm sampling is completed, the LMS continues to work, the temperature of the optical frame could reach a maximum value of 80.6 °C. At the end of this 48-h working phase, the temperature would be as high as 70.4 °C. The temperature simulation curve is shown in Fig. 14.

Regarding actual in-flight observations, the temperature conditions were better than expected. When the dustproof mechanism was unlocked, the temperature of the LMS optical frame was 18.34 °C. When robotic-arm sampling began, the temperature of the optical frame was 34.15 °C. In the simulation, the robotic-arm was assumed to sampling every two hours, and the temperature of the LMS optical frame rose slowly; while the sampling process was accelerated on lunar surface, about once per hour, so the temperature rose faster than simulated due to the rapid sampling in the early stage of in-flight operation. The temperature rose to the highest – 69.81 °C 13-hours after landing on the Moon, which was close to the upper limit of operating temperature. After short-term heat dissipation of about five hours, LMS carried out observation at the sampling points again, until finishing the full-spectral observations for the arranged locations. The temperature changes in-flight is shown in Fig. 14.

4 Performances

The LMS flight model (FM) was fully assembled, tested, and calibrated at SITP. Its performance was characterized, and multiple samples of interest were analyzed.

4.1 Spectral Performance

To acquire accurate spectral information of the sampling area, spectral calibration was performed pre-flight using a monochromator (Horiba iHR320), as shown in Fig. 15. The monochromator was calibrated with a Hg/Ne–Ar source, and the collimated mono-light beam entered the optical system of the LMS as shown in Fig. 15.

After calibration and confirmation on the ground, the spectral range of the LMS was found to be 480–3,200 nm. The spectral resolution was 2–12 nm in the visible channel, 3–12 nm in the NIR channel, 7–24 nm in the SWIR channel, and 10–25 nm in the MWIR channel, as shown in Fig. 16. Meanwhile, based on the measured data, the normalized spectral response function model of the LMS was established, as shown in Fig. 17. According to the characteristics of AOTF, the spectral response is a sinc function (Chanover et al. 1998), so the main peak of it was simulated by Gaussian function.
4.2 Radiometric Performance

Radiometric calibration is a process of correlating the digital-number (DN) value measured by a spectrometer against an absolute physical value (e.g., spectral radiance) (Murchie et al. 2007; Chander and Markham 2009). An integrating sphere and a black body were used in laboratory radiometric calibration. Since atmospheric absorption has an impact on LMS spectral responses, especially in the spectral range of 2.5–2.8 µm, a vacuum tank was adopted to improve the accuracy of radiometric calibration. The LMS was installed with DPCU unlocked. Through a two-dimensional scanning mirror, the optical axis of the LMS was pointed to the center of sapphire window in the front of the vacuum tank. The window’s effective diameter is 150 mm, which can meet the total FOV of LMS with the optical path of 0.5 m. An integrating sphere and a black body were placed outside the vacuum tank in sequence, with a custom adapter ring, which has a separate port for connecting the nitrogen pipe. Nitrogen maintained a steady flow during the test. The testing platform is shown in Fig. 18.

By varying the energy level of the integrating sphere or changing the temperature of the black body, standard lights having different energies were allowed to enter the optical system to provide reference for the DN value. The intension inversion model was obtained by linearly fitting the DN value to the reference spectral radiance. The linearity between the response and spectral radiance is shown in Fig. 19. In the same way as VNIS, LMS also presets adjustable integration time series for conditions of different target reflectance and solar altitude angles (Xu et al. 2014).
Fig. 17  Normalized spectral response of LMS for specific monochromatic light sources: (a–b) 480 nm and 780 nm in VIS band, (c–d) 950 nm and 1,450 nm in NIR band, (e–f) 1,400 nm and 2,300 nm in SWIR band, (g–h) 2,200 nm and 3,200 nm in MWIR band, respectively.

Fig. 18  Laboratory radiometric calibration in vacuum tank. (a) LMS is arranged in a vacuum tank. (b) An integrating sphere were setup for spectral range of 0.45–2.5 μm, and a nitrogen pipe was connected at the junction; simplified scheme is shown as (d). (c) An area blackbody was setup for S-MWIR radiometric calibration, and a nitrogen pipe was also used to connect the vacuum tank window; simplified scheme is shown as (e).

The uncertainty of the inversion results was below 6% in 98% of the bands, as shown in Fig. 20. In the vicinity of 480 nm and 2,500 nm, the high uncertainty was mainly caused by the less illuminating of the integrating sphere calibration light source at the edge of
Fig. 19  Linearity of laboratory radiometric calibration. (Left: r-squared of the IR spectral channels. Right: r-squared of the V-NIR imaging channel with 8 integration time series)

Fig. 20  The uncertainty of radiometric calibration

working wavelength range. Meanwhile, the dichroic filter was used for channel segmentation between V-NIR and NIR channels, which introduced high radiometric uncertainty near 925 nm.

The S/N of the LMS was tested and analyzed via ground radiometric calibration, and the results based on optical frame temperature of 30°C and 65°C are shown in Fig. 21, which modeled with 1.0 AU illumination, phase angle of 45°, albedo of 0.09 (average lunar soil albedo), and lunar surface temperature of 300 K.

4.3 Example of Sample Characterization

Different samples of interest were tested with the LMS FM on the ground to verify data performance. These tests were performed under ambient pressure (∼1 atm) and temperature (instrument temperature ∼30°C). The powder samples included olivine, augite, hypersthene, and plagioclase, which are the typical minerals of lunar soil. The Reflectance Factor (REFF) of these samples are shown in Fig. 22 (Li et al. 2019d).
After a successful soft landing and drilling sampling of the LAC, the LMS conducted lunar observations from 21:08 December 1st, 2020 (UTC) until 17:04 December 2nd, 2020 (UTC). First, a multi-spectral full-view mode was adopted to obtain a panoramic picture of the lunar sampling area, resulting in a six-band mosaic scanning spectral image in the VIS channel and 14 bands of point-scanning spectra in the infrared channels (i.e., NIR, SWIR, and MWIR).

In close coordination with the sampling mechanical arm, the LMS conducted full-band observations of the significant targets, the sampling targets, and candidate points and performed in-flight calibration during the intervals of sampling transfer. Thus, in situ spectral data of the second and third actual sampling points before and after sampling, three sampling candidates, and a distinctive rock from the sampling area were acquired during the CE-5 mission.
Fig. 23  REFF image of LMS at 900 nm, using full-view mode. Areas squared in yellow were detected in the full-band mode, and 588 bands were acquired from 480–3,200 nm. The labeled axes are shown as a robotic-arm coordinate system.

Fig. 24  The S/N curves of the LMS’s four channels (based on the lunar sampling area spectral data acquired at 2020-12-01T23:53:17.375 (UTC), with 0.988-AU, phase angle of 77°).

The REFF image of the sampling area is shown in Fig. 23. Since the distance of the observing target varies, the spatial resolution of the image is 0.4–1 mm.

Based on the lunar surface measurement data, the measured S/N of the single machine is shown in Fig. 24. The measurement conditions are 0.988-AU, the phase angle is 77.0°, and the temperature of the optical frame was about 40°C.

6 Conclusions

This paper described the design, operation, and performance of LMS onboard CE-5, China’s first unmanned lunar-surface sampling return mission. The LMS consisted of an OMU, which performed observations at a spectral range of 480~3,200 nm, scanning in two directions. Its DPCU protected the instruments from lunar dust and provided in-flight calibration.
The EU was fully capable and successfully controlled all devices. Focusing on the lunar sampling area, the LMS has completed multi-spectral imaging and hyperspectral detection missions. The results will be used for mineralogical composition and distribution analyses, fine reconnaissance of lunar-soil characteristics and comparative studies of laboratory lunar-soil samples collected on Earth. Subsequently, the LMS will also be applied to the Chang’E-6 sampling return mission. Meanwhile, the technology of LMS has been used for laboratory microspectroscopy and analytical studies of lunar return samples. Furthermore, LMS-related technologies may also be used in future Chang’E-8 missions.

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Author Contribution Study conception and design were performed by Zhiping He, Jianyu Wang, Chunlai Li, Gang Lv, Liyin Yuan, and Rui Xu. Material preparation, engineering development, data collection, and analysis were performed by Zhiping He, Chunlai Li, Gang Lv, Rui Xu, Liyin Yuan, Sheng Xu, Jian Jin, Zhendong Wang, Feifei Li, Rong Wang, Meizhu Wang, Wei Pan and Jie Yang. The manuscript was written and edited by Rui Xu, Chunlai Li, Zhiping He, Feifei Li, Meizhu Wang, Liyin Yuan, Gang Lv, Jian Jin and Jianan Xie. This work was supervised by Zhiping He, the principal investigator of this project. All authors have read and approved the final manuscript.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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