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IN-FLIGHT AND ON-ORBIT CALIBRATION OF LUNAR IMAGING SPECTROMETERS – A REVIEW

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Abstract

Lunar imaging spectrometers play a leading role in studying the Moon's mineral composition. The accuracy and reliability of the acquired data depend on the calibration process. Key stages of it include laboratory calibration, in-flight validation, on-orbit calibration, and cross-calibration. During these stages, various techniques and methods are used for calibration to achieve higher radiometric accuracy when recording the spectral reflective characteristics of materials in scenes from the lunar surface. These methods include capturing well-known calibration astronomical targets and calibration sites and comparing data from previous lunar surface studies obtained from orbital devices or ground-based telescopes. Other methods are capturing the Earth's atmosphere and utilization of on-board sources, such as lamps with a standardized emission spectrum. This paper reviews the techniques and methods utilized for in-flight and on-orbit calibration of lunar imaging spectrometers, drawing from an extensive overview of referenced science papers.

Introduction

Spectroscopy is an essential analytical method used to investigate material composition and related phenomena by observing the interactions between light and matter [1–3]. A notable benefit is its ability to ascertain composition remotely without requiring direct physical contact [4, 5]. The primary role of an imaging spectrometer is to identify materials or terrestrial features based on their spectral signature. The imaging component essentially acts as a map that displays the spatial location of these spectra, enabling comprehensive mapping and analysis of planetary surfaces [6]; it also finds wide application in Earth observation research, ranging from agricultural studies to wildlife population observation [7, 8]. To ensure precise spectroscopic measurements, it is essential to have a high signal-to-noise ratio (SNR), high calibration accuracy, and high response uniformity [9].

This article specifically focuses on the methods applied for in-flight, on-orbit, and on-board validation of the laboratory calibration of imaging spectrometers used in the SMART-1 (ESA), KAGUYA (SELENE) (JAXA), Chang'E-1 (CNSA), Chandrayaan-1 (ISRO), and Chandrayaan-2 (ISRO) Moon missions. The specific instruments discussed include SIR (SMART-1 Infra-Red Spectrometer) [10], SP (Spectral Profiler onboard KAGUYA (SELENE) [11], IIM (Interference Imaging Spectroradiometer onboard Chang'E-1) [12], HySI (Hyper Spectral Imager onboard Chandrayaan-1) [13], SIR-2 (Near Infrared Spectrometer onboard Chandrayaan-1) [14], M3 (The Moon Mineralogy Mapper onboard Chandrayaan-1) [9], and IIRS (Imaging Infrared Spectrometer onboard Chandryaan-2 orbiter) [15]. Each of these spectrometers has its advantages and disadvantages, leading to specific characteristics in the acquired dataset. These datasets undergo specific processing and calibration before being prepared for use. In some cases, there were disruptions in the acquired spectral data, which imposed limitations on their usage. The science teams, dedicated to each instrument developed custom calibration methods and mathematical algorithms to normalize the registered output data and better understand the effects and characteristics of the imaging spectrometers.

The success of an imaging spectrometer relies on its design, built-in components, alignment, calibration, and stability during and after launch in the operational space environment [16]. These factors contribute to enhanced performance in terms of spectral, radiometric, spatial, and uniformity characteristics, which are critical for the calibration. It is paramount to verify the instrument characteristics measured during laboratory calibration after launch [17]. This is achieved by utilizing pre-launch measurements for characterization and observing well-known astronomical targets during flight to ascertain the effects of the space environment on imaging spectrometers [18]. The calibration process includes laboratory characterization and techniques for in-flight, on-orbit, and on-board characterization and validation. The survey aims to compile and present different calibration targets and methods employed in the reviewed imaging spectrometers' in-flight and on-orbit calibration process.

Development, alignment, testing, and calibration

The imaging spectrometer components are aligned and tested to ensure that its opto-mechanical, thermal, and electronics subsystems meet the science measurement requirements. The laboratory testing and calibration process is improved by utilizing a thermos-vacuum chamber, which simulates space vacuum conditions and a wide range of temperature fluctuations. This chamber allows for evaluating the instrument's performance under challenging low Moon orbit conditions, where temperatures can range from 400 K to 70 K when not illuminated and up to 400 K under direct illumination [9, 14, 15].

To accomplish this, a series of full imaging spectroscopic light measurements are conducted through calibration cold cycles in a thermal vacuum chamber for alignment and calibration purposes. Within this thermal vacuum chamber, the imaging spectrometers observe spectral, radiometric, and spatial illumination sources that can be traced back to absolute standards at operational temperatures. Laboratory measurements and calibrations are performed to understand the intrinsic effects of the spectrometer and to offset these effects during subsequent calibration processes. Thorough lab analysis leads to the development of algorithms that can effectively correct a sensor's output and enhance its performance [19].

In-flight, on-orbit, and onboard confirmation of calibration and measurements

Human-made devices deployed in space are exposed to intense cosmic and solar radiation, potentially damaging the equipment. Fortunately, the Earth's atmosphere and geomagnetic field serve as protective shields against these harmful effects. However, devices in space must still endure severe vibrations and the vacuum environment to reach their designated research destinations. Once in space, these devices face many challenges, including wide temperature variations, heightened galactic and solar radiation, and the constant risk of colliding with high-energy particles, micrometeoroids, and space debris. Unlike Earth, the Moon lacks an atmosphere and a robust magnetic field, leaving devices in lunar orbit more vulnerable to these hazardous conditions. As a result, the harsh conditions in space can disrupt the components of these instruments, hinder their standard functionality, and cause damage [20].

Given the challenging launch process, the harsh environment of space, and the lengthy journey to the Moon, it is essential to calibrate imaging spectrometers by comparing their in-flight and on-orbit data with the preflight calibration results. The preflight calibration is a benchmark for the spectrometer's properties, while in-flight and on-orbit activities help update these calibrations to ensure accurate measurements of the object's surface [21].

The process of obtaining data from Earth observations (Fig. 1.) while the device is in-flight or in orbit is crucial for the precise validation and calibration of an imaging spectrometer's spectral performance and dark data (Fig. 2.). To achieve this, observations of Earth are conducted to record the spectral signature of the Earth's atmosphere, which is influenced by various gases such as O2, CO2, and water vapor. These absorption features in the atmosphere are then utilized to evaluate the spectral calibration of the imaging spectrometer while in orbit, ensuring consistency with the pre-launch laboratory spectral calibration. The accuracy of the imaging spectrometer's measurements can be validated using the MODTRAN (MODerate resolution atmospheric TRANsmission) [22] radiative transfer code, which involves comparing the calibrated spectra from the imaging spectrometer with the modeled spectra from MODTRAN. MODTRAN, developed through a partnership between Spectral Sciences Inc. and the Air Force Research Laboratory, is integrated into various operational systems and research sensors to process multi- and hyperspectral remote sensing data requiring atmospheric correction [23]. This goes back to the HITRAN database of atmospheric gas absorption lines [24] and the laser calibration sphere, which has known laser wavelengths. HITRAN (High-Resolution Transmission Molecular Absorption Database) is a collection of spectroscopic parameters used by several computer programs to simulate the transmission and emission of light in the Earth's atmosphere. It was developed by the Atomic and Molecular Physics Division at the Harvard-Smithsonian Center for Astrophysics and is accessible to users on HITRANonline [25]. Aligning the positions of the wavelengths of the detected spectral absorption bands in Earth's atmosphere with those of the modeled ones provides crucial confirmation of the spectrometer's in-flight spectral calibration [9, 15].

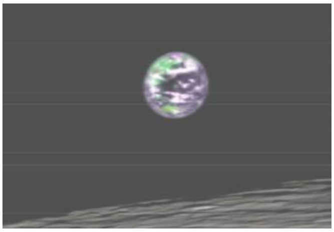

Fig. 1. Image of Earth taken from the Moon's orbit for M3 spectral calibration validation [26]

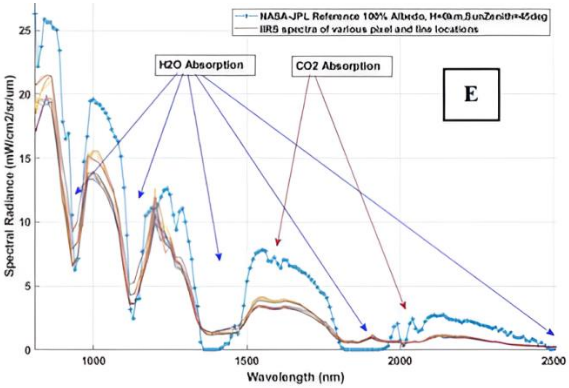

Fig. 2. Spectral radiance signature is graphed in conjunction with reference or standard spectra to compare the positions of spectral absorption bands [15]

To perform in-flight calibration, spectra can be captured from celestial bodies such as Jupiter (Fig. 3) and bright stars. Additionally, dark frames of unilluminated surfaces and areas of the dark sky can be utilized to test and confirm the calibration carried out on the ground [10]. The uniformity of the spectral Instantaneous Field of View (IFOV), which refers to the position of the IFOV relative to wavelength, is evaluated by analyzing bright targets in shadowed Polar Regions of datasets. These profiles, see Fig. 2, are normalized to a high radiance value, and their alignment across different spectral regions as they intersect with a brightly illuminated sample is used to validate the spectral IFOV uniformity of imaging spectrometers in lunar orbit [9].

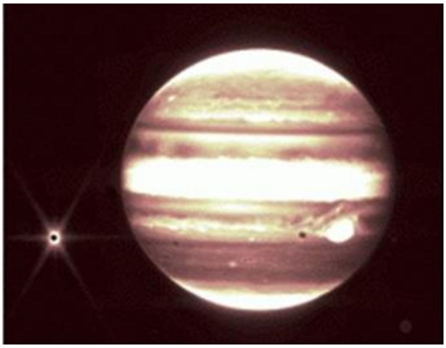

Fig. 3. The James Webb Space Telescope's NIRCam instrument, using a 2.12 micron filter, captures images of Jupiter, positioned in the center, and its moon Europa, to the left [Image credit: NASA, ESA, CSA, and B. Holler and J. Stansberry (STScI), 27]

During flight, radiation exposure can affect the dark current in detectors. While the overall rate of dark current remains constant, there is an increase in the number of pixels that exhibit a significant rise in responsivity (hot pixels) and multi-stable responsivity (RTS pixels). To account for this, bad pixel maps can be continuously updated to reflect the growing count of these pixel populations. The noise level of the imaging spectrometer is assessed by examining every pixel of the focal-plane array for new dead or damaged pixels. This is done using nighttime data from multiple images with lower exposure rather than capturing a single image with a long exposure time [28]. In addition, calibration characteristics obtained during the laboratory phase are utilized to evaluate the wear of the sensor and identify any inconsistencies in the collected data. This is achieved by recording calibration sites sequentially under consistent lighting conditions to track data changes and highlight any degradation in the sensor and its calibration. Regular observations conducted before and after each lunar day during the night [11] are used to make corrections for dark-level noise. Moreover, observations from deep space, nighttime [13, 29], and the dark side of the Moon can also contribute to the dark calibration process [26]. These observations aid in removing or correcting dark offset in the data.

The process of lunar calibration involves using the Moon's surface as a reference point for calibration. The reflectance of the Moon's surface is based on measurements obtained by Earth-based telescopes and previous lunar missions. Over a billion years, the Moon's surface reflectance has exhibited less than 1% variance, indicating high stability [30]. It is assumed that the Moon's phase of active volcanism concluded around 1.2 billion years ago during the Copernican period, and thus, the basic layout of albedo units on the Moon's surface is believed to have remained constant since then. With its high stability, the Moon's surface reflectance serves as a reliable photometric benchmark. Notably, the Moon's surface exhibits significant brightness variation at a phase angle $|\alpha| \leq 7°$, which is attributed to the strong backscattering or brightness opposition effect. This brightness dependency on the phase angle provides valuable insights into the surface's composition and microstructure [31].

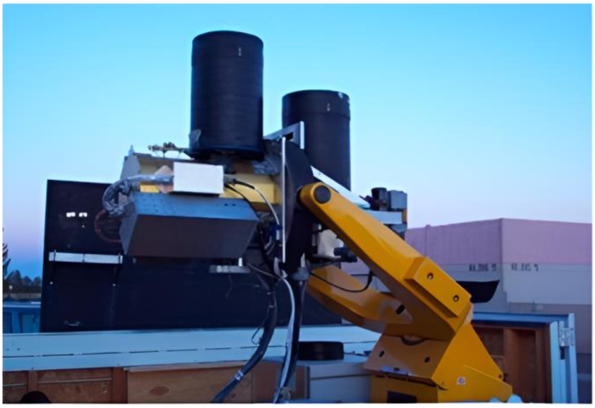

Fig. 4. RObotic Lunar Observatory (ROLO) at U.S. Geological Survey at the Flagstaff Science Campus in Flagstaff, Arizona [32]

To enable the Moon to serve as a radiometric calibration standard for spacecraft instruments in Earth’s orbit and to develop a radiometric model of the Moon, NASA funded the U.S. Geological Survey at the Flagstaff Science Campus in Flagstaff, Arizona. This funding led to the establishment of the ground-based RObotic Lunar Observatory (ROLO) (Fig. 4.). The ROLO’s lunar spectral irradiance specification is based on a database of spatially resolved radiance images of the Moon. These images were obtained from an observatory specifically designed and constructed for this project. Over more than six years, ROLO collected observational data, covering phase angles from near eclipse to typically 90 degrees before and after a full Moon, and encompassing a broad spectrum of observable libration angles. The radiometric model of the RObotic Lunar Observatory (ROLO) can estimate the Moon’s brightness (irradiance) with an approximate precision of 1% over a broad phase range. This precision is advantageous for calibrating imaging spectrometers that are in orbit around the Moon [33]. The validation of spectral calibration while in orbit is achieved by comparing the location of absorption lines of pyroxene and olivine, as measured in the spectra of the imaging spectrometer. The validation of radiometric calibration is done by comparing measurements from imaging spectrometers with those from ROLO [9, 34]. The data sets are searched to find measurements with similar illumination and observational conditions for comparison. Data from an internal calibration lamp, which offers radiometric calibration details independent of lunar surface calibration sites, assists in tracking the radiometric sensitivity and spectral positioning of each pixel. This method aids in distinguishing variations in sensitivity between data collected during flight and prior to flight. It also allows for updating the master flats (reference image) and the responsivity of each pixel throughout the mission [11, 28 and 35]. Lunar observations made by lunar on-orbit imaging spectrometers can be validated by comparing them with data from other instruments that observe the moon, including Earth-based telescopes.

The imaging spectrometer calibration can be validated by monitoring specific lunar calibration sites, such as Apollo 16 (Fig. 5), Mare Serenitatis 2 (Fig. 6), and other areas on the lunar surface. These sites have recognized near-infrared spectra derived from soil samples or telescope observations that have been adjusted for atmospheric influences [11, 13].

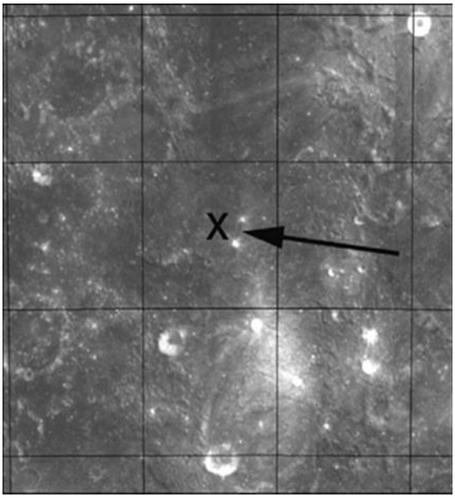

Fig. 5. Image of Apollo 16 Central Nearside Highlands [35]

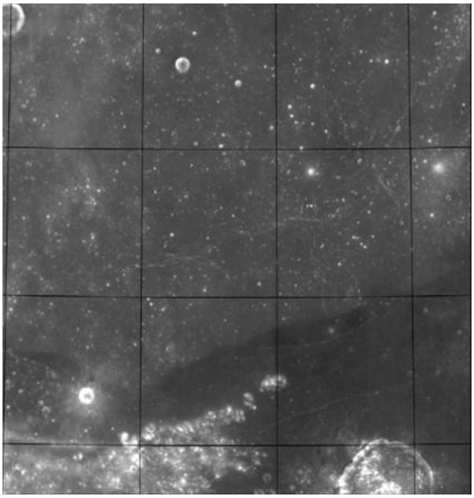

Fig. 6. Image of Mare Serenitatis [35]

Following global discussions, at scientific forums, under the COSPAR (Committee on Space Research) program in Beijing, and at the 8th International Conference on Exploration and Utilization of the Moon, the Lunar International Scientific Calibration/Coordination Targets (L-ISCT) (Fig. 7.) [35, 36], were proposed. This list of eight lunar calibration sites aims to enable cross-calibration of various multinational instruments, with the goal of creating a globally calibrated dataset for comparison with other instruments. Five of these targets were identified and discussed in depth at the 8th International Conference on Exploration and Utilization of the Moon, following their presentation at the COSPAR meeting in Beijing. This concept received international endorsement and was included in the Lunar Beijing Declaration [37]. The Apollo 16 site was selected first on the list of lunar calibration sites as part of the international collaboration and coordination effort. Given the inevitable limitations of spacecraft resources, the site was chosen for its optimal calibration characteristics, which allow calibration of instruments performing orbital imaging, UV-Vis-NIR, gamma-ray spectroscopy, X-ray and neutron spectroscopy, altimetry, thermal, radar, and microwave imaging. The Apollo 16 site is a large area of relatively uniform feldspathic highlands on the lunar nearside. This knowledge is derived from the analysis of returned lunar samples. The site has become crucial for calibrating lunar spectroscopic data, with spectra of representative lunar soil sample 62231 [38, 39] collected and returned to Earth by the Apollo 16 crew. These samples were analyzed under laboratory conditions by the Reflectance Experiment Laboratory (RELAB) [40] and included in the Lunar Sample Compendium (https://curator.jsc.nasa.gov/lunar/lsc/ index.cfm) serving as ‘‘ground truth’’ for data obtained by remote sensing [37]. The remaining calibration targets on the list include: #2 Lichtenberg crater; #3 Apollo 15 Hadley Rille (Fig. 8.); #4 South Pole-Aitken Basin Th-anomalies; #5 Tycho crater; #6 Polar Region with shadows; #7 North Schrodinger; #8 Mare Serenitatis. Each of these proposed calibration targets is distinguished by its unique features and is linked to significant unresolved scientific inquiries.

This calibration method leads to better results than previous methods, such as observing stars or star patterns. By observing calibration sites, data from remote sensing of the Moon can be calibrated using laboratory-tested spectral reflectance characteristics of lunar surface samples. Aligning this data with data from previous lunar missions and data recorded by ground-based telescopes greatly aids consistent interpretation and analysis of lunar surface mineralogy.

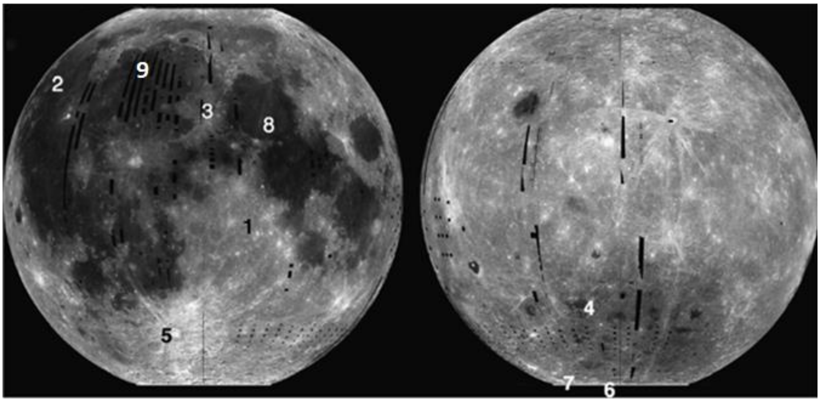

Fig. 7. A lunar map highlighting the eight suggested ISCT areas, each marked by a number, along with the CE-3 landing site, which is proposed as a new calibration site and labeled as #9 [35]

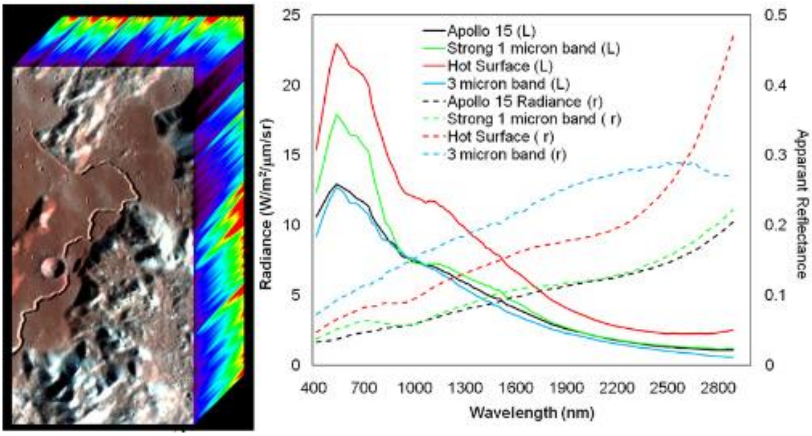

Fig. 8. M3 image of the Apollo 15 landing area, including the Hadley Rille [26]

The Visible-Near Infrared Spectrometer (VNIS) on China's Chang'E-3 (CE-3) mission's "Yutu" rover recorded the Moon's first in situ reflectance. The landing site of CE-3 is proposed as a new calibration site (Fig. 9.). The VNIS in situ reflectance indicates that the CE-3 landing site has a very low absolute reflectance, implying a high concentration of FeO and TiO2. The VNIS measurements fall between those from the Lunar Reconnaissance Orbiter Camera Wide Angle Camera (LROC WAC) and Spectral Profiler (SP), and those from the Moon Mineralogy Mapper (M3) and Imaging Infrared Mapper (IIM). Compared to commonly used calibration sites like MS-2 and Apollo 16 Highlands [41], the CE-3 calibration site is much younger and less impacted.

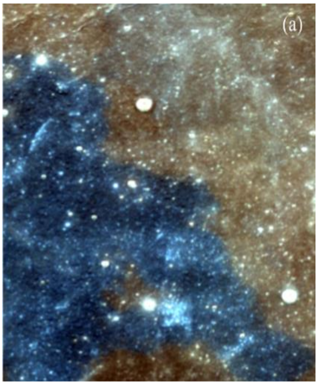

Fig. 9. Image of CE-3 calibration site [41]

Data from the Clementine mission can also be utilized. This can be achieved either by using Clementine's five channels that fall within the instrument's spectral range or by using Clementine UVVIS data for consistency checks [42].

The calibration models and laboratory tests primarily focus on the structures of the imaging spectrometers, neglecting the stray light from other parts of the spacecraft. However, images from in-flight system health checkouts have shown that, under specific illumination geometries, imaging spectrometers are susceptible to stray light reflecting off other instruments and structures on the spacecraft. A thorough stray light model of the entire spacecraft is utilized to mitigate these effects and examine various observational conditions. Such analyses enable the determination of spacecraft orientations relative to the Sun that are most beneficial for reducing stray light during critical observations throughout the mission. These predictions are validated in flight by capturing images with the spacecraft positioned in a range of orientations surrounding the anticipated optimal conditions [28].

Conclusion

This study underscores the critical role of comprehensive calibration in guaranteeing the accuracy of data acquired by lunar imaging spectrometers. Our key findings reveal that custom-developed corrections effectively address performance variations during flight and orbit. Earth's atmosphere spectral signature observations, lunar models, and dedicated calibration targets facilitate data calibration. Additionally, internal calibration lamps, Clementine mission data, and telescope observations offer valuable validation sources. Importantly, in-flight and on-orbit calibration strategies tackle instrument stability, spectral registration, stray light, and environmental effects. Challenges such as limited access to calibration standards, variations in lunar surface composition, stray light contamination, and the visibility of calibration targets persist. Continuous advancements in calibration methodologies are essential for enhancing the accuracy and reliability of lunar imaging spectrometers, ultimately paving the way for gaining deeper insights into the properties, composition, and geological history of the Moon.

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КАЛИБРИРАНЕ НА ОПТИЧЕСКИ СПЕКТРОМЕТРИ ПО ВРЕМЕ НА ПОЛЕТ И В ОКОЛОЛУННА ОРБИТА - ОБЗОР

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Резюме

Оптическите спектрометри имат водеща роля в изследването на минералния състав на Луната. Точността и надеждността на данните, регистрирани от тези инструменти, зависят от процеса на калибриране. Ключови етапи от него заема лабораторното калибриране, валидирането по време на полет, в орбита и насрещното калибриране. По време на тези етапи се използват различни техники и методи за калибриране с цел постигане на по-висока радиометрична точност. Тези методи включват заснемане на земната атмосфера, на добре известни астрономически цели и площадки за калибриране. Съпоставка с данни от предишни изследвания, получени от орбитални апарати или земни телескопи. Приложение намират и бордови източници за калибриране, като лампи със стандартизиран спектър на излъчване. Обзорът представя преглед на техники и методи, използвани за калибриране на оптически спектрометри, в полет към Луната и в лунна орбита, подготвен въз основа на обширен преглед на цитираната реферирана и нереферирана научна литература.