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Reviews

GROUND TRUTH CALIBRATION OF LUNAR IMAGING SPECTROMETERS – A REVIEW

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Abstract

Imaging spectrometers provide valuable data on the composition and history of planetary surfaces. Lunar samples returned to Earth reflect the characteristics of the specific lunar region from which they originate. They are used to calibrate data containing spectral reflective characteristics. Lunar sample 62231, taken and returned to Earth by the astronauts from the Apollo 16 mission, is characterized as a mature highland soil. It is standardly used for calibrating data recorded by optical spectrometers (0.3-3µm), studying the lunar surface. The process of analyzing and interpreting data on the lunar surface's mineral composition is greatly enhanced by maintaining consistent calibration and aligning with prior studies. This paper provides a review of the application of sample 62231 from the lunar surface and various considerations and reserves associated with it, drawing from an extensive overview of referenced science papers.

Introduction

Imaging spectrometers provide valuable insights into the composition and history of planetary surfaces by allowing for detailed mapping and analysis. The process of correcting imaging spectrometer data begins with the development, planning, and implementation of laboratory and on-board characterization methods. These methods are crucially influenced by the instrument's design, construction methods, and performance requirements [1]. Every imaging spectrometer is subjected to laboratory, pre-flight, and in-flight calibration. The data collected is then scientifically calibrated. These collective calibration procedures constitute the calibration pipeline, which is designed to convert raw digital data into spectral radiance in physical units, measured in watts per square meter per micrometer per steradian ($W\ m^{-2}\ \mu m^{-1}\ sr^{-1}$), and subsequently to reflectance spectra. This is achieved through the use of pre-launch characterization measurements and in-flight observations of well-known astronomical targets [2]. The imaging spectrometers are engineered to enable scientists to fulfill their intended scientific objectives. During the laboratory phase, its components are aligned and the design is tested for basic functionality. This is done by ensuring that its opto-mechanical, thermal, and electronics subsystems meet the science measurement requirements. These processes are accomplished by conducting a series of comprehensive imaging spectroscopic light measurements during calibration cold cycles inside a thermal vacuum chamber, which is used for alignment and calibration [3]. Both ground-based and pre-flight calibrations and measurements are performed to understand the effects of the spectrometer. This knowledge is then applied to mitigate these effects during the scientific data calibration process.

Ground truth calibration

Lunar samples returned to Earth represent a significant asset, allowing scientists to accurately measure their reflectance properties in laboratories on Earth. The Apollo program, Luna, and Chang'E 5 missions brought back lunar minerals and soils [4]. The Apollo samples were measured by the Reflectance Experiment Laboratory (RELAB) for their reflectance spectra in the visible and near-infrared spectral range [5]. These samples, after meticulous examination and selection, can represent the characteristics of the specific lunar region from which they originate. They serve as the fundamental reference ‘ground truth’ for infrared spectral characteristics [4]. The Apollo 16 site, due to the returned lab-tested mature soil sample 62231 [6] (Fig. 1) and its consistent soil composition, has been chosen as a calibration target on the Moon, as well as soil sample 62231 as a calibration standard [7]. These samples’ diagnostic spectral absorption features form the foundation for using imaging spectrometers to map the composition of the lunar surface. The raw data collected by the instruments are transformed into reflectance measurements through a series of data processing steps that incorporate lab reflectance measurements of the soil sample. By analyzing the entire spectral shape, minerals and other components can be identified, and their abundances can be estimated even when there are compositional mixtures present [3].

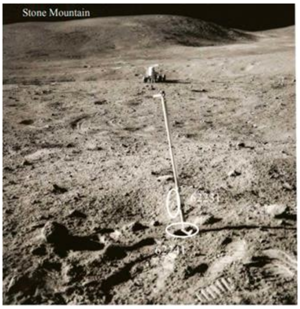

Fig. 1. Photo of the Buster Crater rim from the Apollo 16 mission, showing the location where the 62231 and 62241 soil samples were collected [6]

Moreover, it was found that using Apollo soil sample 62231 as a calibration standard provided more accurate outcomes for telescopic reflectance measurements than using ‘solar-like’ stars or stellar models. Following this, the Apollo 16 calibration site and Apollo 16 soil sample 62231 were used for calibrating the remotely sensed data of Clementine’s mission and enhanced understanding of it by permitting more precise observations and measurements [5]. The imaging spectrometers’ reflectance spectra have been modified to align with the spectral characteristics of lunar soils in the visible to near-infrared range, based on detailed laboratory analysis of lunar samples [8]. Prior to 1980, an area in Mare Serenitatis, referred to as MS2, was utilized as a calibration site. This was because there were no proximate albedo features that could contribute unwanted inaccurate data if the area was not precisely located through the Earth-based telescope.

The interpretation and analysis of the lunar surface mineralogy greatly benefit from aligning with previous observations. Lunar soil sample 62231, from the Apollo 16 mission, which is a mature highland soil, has been used as the standard for calibrating lunar remote sensing data in the visible to near-infrared range. This began with telescopic observations from Earth and continued with the Galileo and Clementine lunar missions. This correction provides lunar remote sensing data that has been calibrated using ground truth. As a result, the imaging spectrometers that have remotely captured the lunar surface’s reflectance spectra part of the payload of Clementine, SMART-1, SELENE, Chang’E-1, Chandrayaan-1 missions have been modified to align with the spectral characteristics of sample 62231 in the visible to near-infrared range based on detailed laboratory analysis [5, 8-12] maintaining consistency with previous lunar missions and earth-based telescopes. The Moon Mineralogy Mapper (M^3) L2 data in the Planetary Data System is delivered without the application of ground truth factors. These factors are made available to the users, who then have the discretion to decide if they want to apply these factors, and must do so independently [8, 13, 14]. According to the M^3 team, the most dependable reflectance dataset is global mode data when the ground truth correction is applied, particularly for wavelengths less than approximately 1500 nm [8]. The Apollo 16 calibration site, situated about 10 km west of the Apollo 16 landing area, is predominantly used for both terrestrial telescopic observations and orbital data calibration. This preference is due to the belief among researchers that its spectra could be mirrored by the lab spectra of Apollo 16 bulk soil sample 62231.

Discrepancies in the ground truth reflectance spectra

Comparative research reveals that the lunar radiance values measured by remote sensors at landing sites are not as high as those estimated from laboratory measurements of soil samples returned from the Moon. This discrepancy is largely due to the fact that laboratory measurements of lunar soils are unable to replicate or preserve the fine structure of the lunar regolith found in its natural space environment especially the space weathering due to deposition of nanophase Fe0 metal which weakens the Fe2+ absorption band around 1.0 μm significantly darkens the lunar surface and suppresses spectral bands [15]. In every instance, laboratory measurements of lunar soils have shown higher brightness levels than those measured in the Moon's natural environment. The data calibrated using laboratory-measured reflectance spectra of 62231 lunar soil sample as a reference point revealed differences in brightness between soil samples returned from the Moon and the Apollo 16 mission [16, 17]. An eloquent example is the reflectance measurements of the area nearer to the Apollo 16 lander, indicating an increase in soil brightness as it becomes closer to the lander due to regolith disturbance by rocket exhaust during descent. Reflectance properties are affected by regolith properties such as roughness, compactness, temperature, vacuum, and maturity. The topmost lunar surface is highly mature, which significantly reduces reflectance. Therefore, lab simulations using lunar samples cannot accurately represent pristine regolith in a lunar environment. The lab reflectance of returned samples is much higher than that of pristine regolith and cannot accurately represent the actual lunar surface [17]. Unfortunately, maturity is a complex concept, making it difficult to compare the maturity between in situ and laboratory samples. Therefore, the Lunar landing mission Chang'E-3 brought to the lunar surface the "Yutu" rover, which, using a Visible-Near Infrared Spectrometer (VNIS), carried out measurements of the lunar surface in situ. The Chang'E-3 landing site is found to be a young and homogeneous surface and is suggested as a new calibration site.

Generally, in the dataset from the imaging spectrometers, each identified rock type and its related chemical properties represent an average across the entire pixel, offering only a generalized perspective of these intricate geological features on the ground. The lunar regolith, or moon soil, is primarily composed of local bedrock. However, it also contains small quantities of other crustal lithologies that have been transported both laterally and vertically due to the impact of meteorites. This bombardment also leads to the creation of various forms of impact glass, including glassy-mineral structures known as agglutinates. Additionally, the regolith includes mineral debris from the impacting bodies and volatile compounds that have been deposited on the surface through the arrival of asteroids, comets, and highly charged particles [4]. The imaging spectrometers that have remotely sensed the lunar surface have a spatial resolution of up to 70 m/pixel, which is the maximum resolution of M3 [3]. Lunar probes are physically small, with dimensions in centimeters. This scale difference shows that the light reflected from ground samples constitutes a minor percentage of the total data captured in a single pixel of a million square centimeters and therefore leads to questions about how thorough and accurate a returned lunar sample represents the remotely sensed surface. Indeed, samples of lunar regolith can offer valuable insights into the geographical distribution of various geological formations. They can also shed light on the chemical and mineralogical interactions between different terrains and crustal depths. However, calibrating remote sensing methods for analyzing the composition of planetary regolith is challenging and remains an ongoing process [18, 19]. The absolute reflectance value of the Moon has been a long-standing puzzle in the field and remains an unresolved issue [17].

Lunar meteorites as ground truth

Orbital spacecraft equipped with imaging spectrometers have revealed that our current lunar sample collections are from a compositionally unique area of the Moon. Lunar meteorites are samples of the moon’s surface that arrived on Earth after a crater was formed on the lunar surface. Unfortunately, their exact origin is unknown, and they lack geologic context. Lunar meteorites with high thorium (Th) concentrations are believed to have originated in or near the Procellarum KREEP Terrane. Most lunar meteorites seem to have originated outside of this area, as they typically contain less than 1 part per million of Th. This distribution is logical, suggesting that most lunar meteorites are rocks from nearly random locations on the lunar surface, where radioactivity levels are generally low [19]. The lunar meteorites contain materials that were not collected by the Apollo, Luna, and Chang’E-5 missions, making them a valuable addition to the collection of materials that can be used as ground truth. With thorough research and precise measurements, the lunar meteorite samples should offer a more varied dataset that can be utilized for calibration and to provide limitations on scientific analyses [20]. Overall the Apollo, Luna and Chang’E-5 missions touched down in a small, geologically intriguing area on the near side of the Moon that is not representative of the Moon’s overall composition (Fig. 2). The rocks gathered during these missions are rich in naturally occurring radioactive elements such as potassium (K), thorium (Th), and uranium (U). These rocks are referred to as “KREEP” due to their high concentrations of K and other elements like rare-earth elements (lanthanum and cerium) and phosphorus (P). These probes serve as our representatives and are currently the best tools we have for gaining insight into the geology of the Moon within the limited area of the Procellarum KREEP Terrane on the near side of the Moon.

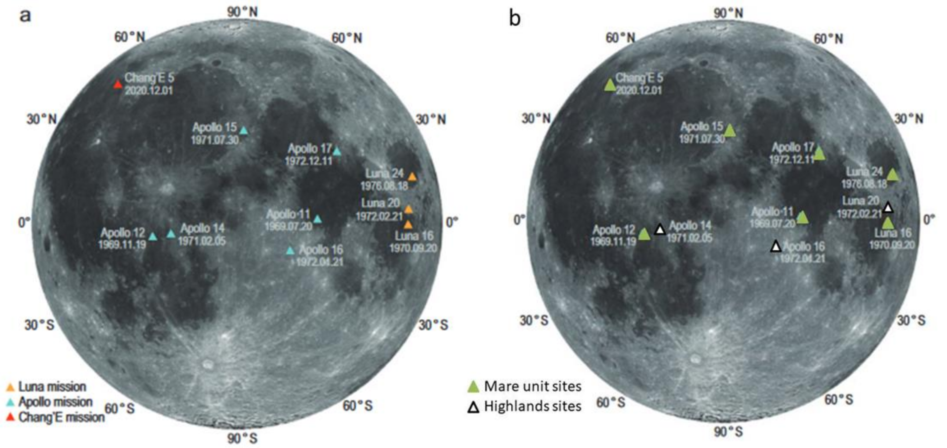

Fig. 2. Map (a) showcasing the returned samples from the Moon, with all Apollo mission landing sites marked in blue, Luna mission sites in orange, and Chang'E mission in red. Identical map (b) displays more unit sites marked with green symbols, and highlands sites indicated by orange symbols [21,22].

Conclusion

The Apollo 16 calibration site, located approximately 10 km west of the Apollo 16 landing area, is primarily used for calibrating both terrestrial telescopic observations and orbital data. This is largely because researchers believe that its spectra closely match the laboratory spectra of the Apollo 16 bulk soil sample 62231. Using the Apollo soil sample 62231 as a calibration standard delivers more precise outcomes for telescopic reflectance measurements compared to using 'solar-like' stars or stellar models. This correction provides lunar remote sensing data that has been calibrated using ground truth. The calibration standard soil sample 62231 can represent the characteristics of the specific lunar region it originates from and serve as the fundamental reference 'ground truth' for infrared spectral characteristics. The consistent interpretation and analysis of lunar surface mineralogy are greatly enhanced by aligning with the observations made by previous lunar missions and Earth-based telescopes. These samples are currently the best we have for gaining insight into the geology of the Moon. Users should exercise caution when utilizing the data sets and implement corrections carefully.

In relation to the M^3 data, the decision to apply the corrections rests with the users, and they are expected to carry out this task independently if deemed necessary. Still, calibrating remote sensing methods for analyzing the composition of planetary regolith is challenging and remains an ongoing process.

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КАЛИБРИРАНЕ НА ОПТИЧЕСКИ СПЕКТРОМЕТРИ, ИЗСЛЕДВАЩИ ЛУННАТА ПОВЪРХНОСТ С НАЗЕМНИ ДАННИ – ОБЗОР

И. Иванов, Л. Филчев

Резюме

Оптическите спектрометри предоставят ценни данни за състава и историята на планетарните повърхности. Лунните проби, върнати на Земята, отразяват характеристиките на конкретния лунен регион, от който произхождат. Те се използват за калибриране на данни, които съдържат спектрални отражателни характеристики. Лунна проба 62231, взета и върната на Земята от космонавтите от мисията Аполо 16, е характеризирана като зряла високопланинска почва. Тя стандартно се използва за калибриране на данни, регистрирани от оптически спектрометри (0.3-3μm), изследващи лунната повърхност. Анализът и интерпретацията на данните за минералния състав на лунната повърхност значително се подпомагат от последователното привеж-дане на регистрираните данни в съответствие с предишни изследвания. Обзорът представя преглед на приложението на проба 62231 от лунната повърхност и свързаните с нея различни съображения и резерви. Обзорът е подготвен въз основа на преглед на цитираната реферирана и нереферирана научна литература.