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Estimation of elemental abundances of the lunar regolith using clementine UVVIS+NIR data

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ABSTRACT

In this study we propose a regression model for the estimation of lunar elemental abundances from spectral features extracted from Clementine multispectral imagery in the visible and near-infrared domain. We extract a set of spectral features, including the continuum slope, the FWHM of the ferrous absorption trough near 1000 nm, and the wavelengths and relative depths of the absorption minima and inflection points present in the trough. As a "ground truth" for the elemental abundances we rely on the Lunar Prospector gamma ray spectrometer (LP GRS) data. With respect to the elemental abundances of the Apollo and Luna landing sites independently derived from returned samples, the best examined regression model is a second-order polynomial. The proposed regression-based approach allows an estimation of the elemental abundances of Ca, Al, Fe, Mg, and O at an accuracy of about 1 wt% and some tenths of a weight percent for Ti. We examine the influence of calibration of the Clementine UVVIS+NIR data and find that its effect on the results obtained with the regression approach is minor. Furthermore, we define a three-endmember model which allows the petrographic mapping of the lunar surface materials in terms of their Fe, Mg, and Al abundances. We examine the global distribution of Mg-rich rocks, the distribution of cryptomaria, and the occurrence of aluminous mare basalts in the Frigoris region. A possible regional compositional anomaly in northwestern Oceanus Procellarum is found, which corresponds to an extended area displaying spectral characteristics consistent with mare basalt containing significant amounts of olivine. On local scales, we examine in terms of our regression model the highland craters Proclus and Tycho, the compositionally anomalous central peaks of the craters Copernicus and Bullialdus, and the pyroclastic deposits on the floor of Alphonsus and on the northern rim of Petavius. As a general result, we show that the regression-based approach allows the detection of the main lunar terrain classes and rock types based on multispectral imagery in the visible and near-infrared domain.

1. Introduction

Elemental mapping of the Moon is important for a better understanding of lunar formation and its evolutionary history. Elemental maps of the lunar surface allow the identification of different types of mare basalts and petrographic units in the highlands, to determine the composition of ancient cryptomaria and the South Pole Aitken basin, to search for regions with unusual chemical composition, and to estimate abundances of volatile elements at the lunar poles. Apollo X-ray and gamma-ray spectrometers determined the abundances of Fe, Th, and Al/Si and Mg/Si ratios for equatorial regions of the Moon. Using these data, Davis and Spudis (1985) establish that all the observed elemental abundances could be explained by a mixing of ferroan anorthosite, mare basalts, and KREEP basalts. Due to old volcanic eruptions and mixing by meteoroid impacts, mare basalts also exist in the farside lunar highlands. Lucey et al. (1998, 2000) develop a spectral reflectance technique to map FeO and TiO_2 abundances within an error of about 1 wt% using Clementine data. Optical and near-infrared spectroscopy is a useful and powerful tool for the determination of particle size, maturity, and mineral content of the lunar surface (McCord et al., 1981; Shkuratov et al., 2003; Lucey, 2004).

Global mapping of Th and Fe abundances on the Moon was conducted using low-resolution gamma-ray spectra observed by the Lunar Prospector spacecraft (Lawrence et al., 1998, 2000, 2002, 2003). The most interesting results are the mapping of the distribution of KREEP basalts on the lunar surface, the detection of geochemical anomalies at Tycho crater and in the Compton–Belkovich region, the

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estimation of the elemental composition of the South Pole Aitken basin, and the detection of small-area Th-rich anomalies. Preliminary data about other elements, including O, Si, Mg, Al, Ca, K, U, and Ti are presented by Prettyman et al. (2002, 2006).

In the near future our knowledge about the elemental composition of the Moon will be greatly improved by the efforts of several missions. The European SMART-1 mission carrying the AMIE camera for optical band photometry, an infrared spectrometer and an X-ray spectrometer already performed a study of the Moon. The X-ray spectrometer mapped abundances of Al, Mg, Fe, and Si (Swinyard et al., 2009). The Japanese Kaguya mission studied the Moon from a polar orbit from December 2007 to June 2009. The spacecraft carried gamma-ray and X-ray spectrometers. The X-ray spectrometer was able to map Al, Mg, and Si with complete coverage except polar regions as well as Fe, Ca, and Ti during solar flares (Yamamoto et al., 2008). The Kaguya gamma-ray spectrometer, employing a germanium detector with excellent energy resolution, mapped Th, Fe, O, Si, Mg, Al, Ca, K, U, and Ti abundances (Kobayashi et al., 2005). Similarly, the X-ray spectrometer of the Chandrayaan-1 spacecraft was able to map the abundances of the main elements in the lunar regolith (Crawford et al., 2009).

The global multispectral Clementine UVVIS+NIR data set of the lunar surface has a typical spatial resolution of about 100–150 m per pixel, which is between two and three orders of magnitude higher than those of the available elemental abundance data sets obtained based on X-ray and gamma-ray spectroscopy. Spectral features in the UVVIS and NIR domain are correlated with the abundances of specific minerals—for example, the reflectance ratio R_{450}/R_{750} is known to be indicative of the TiO_2 content of the lunar soil, as pointed out e.g. by Charette et al. (1974)—which are in turn correlated with elemental abundances. A more recent approach to mineralogical mapping with Clementine UVVIS data is described by Shkuratov et al. (2005a), who provide maps of the FeO and Al_2O_3 bulk contents and the contents of these oxides in plagioclase and clinopyroxene. Pieters et al. (2006) compare several statistically optimised formulations describing links between parameters indicative of spectral and mineral properties and apply the obtained expressions to Clementine UVVIS data. This approach allows to estimate the pyroxene abundance and soil maturity parameters as well as to distinguish between low-Ca and high-Ca pyroxenes. A nonlinear approach to the estimation of the TiO_2 content of lunar soils based on artificial neural networks is proposed by Korokhin et al. (2008).

In this study, we estimate lunar elemental abundances based on spectral features derived from Clementine UVVIS+NIR imagery, using Lunar Prospector data as a reference. This approach allows to estimate lunar elemental abundances on the high spatial resolution level provided by the Clementine UVVIS+NIR data set—a similar method is developed by Shkuratov et al. (2005b), which, however, does not make use of Clementine NIR data. We furthermore provide a detailed analysis of the estimated elemental abundances in terms of the three-endmember model proposed by Berezhnoy et al. (2005), perform a petrographic mapping of the lunar surface, and examine several small-scale elemental abundance anomalies.

2. Data sets analysed in this study

2.1. The LP GRS elemental abundance data set

Lunar Prospector gamma-ray spectrometer data give the abundances of the elements Ca, Al, Mg, O, Si, and U on the Moon with a spatial resolution of 150 km, corresponding to a 5 × 5 degrees area. Ti and K data are given with a spatial resolution of 60 km, while Th and Fe data are given with 15 km spatial resolution. The quality of these data sets is good enough for a preliminary analysis. For estimation of the quality of Lunar Prospector data we compare the elemental composition of landing sites measured by Lunar Prospector and by analysis of returned samples. The bulk composition of sample-return sites is taken according to Elphic et al. (2000). There are positive correlations between abundances of all elements, except Si, measured by Lunar Prospector and by the analysis of returned samples. However, Lunar Prospector Si data contradict the Si content in returned samples, as shown by Berezhnoy et al. (2005). The Si content in the western maria is significantly lower according to Lunar Prospector results than the values measured for returned samples. This is an intrinsic property of the LP GRS data due to the applied data model and processing—the underestimation of the Si content leads to a moderate overestimation of the Mg content by several weight percent especially in Th-rich western maria (cf. Fig. 1). Consequently, such systematic errors in the LP GRS abundances also affect the mapping of Mg abundances in this study since the proposed regression technique "mimics" the characteristics of the utilised ground truth (or better: reference) data. This behaviour, however, is inherent in any linear or nonlinear optimisation approach that relates one data set to another, such that it is essential to use bias-free ground truth data once available.

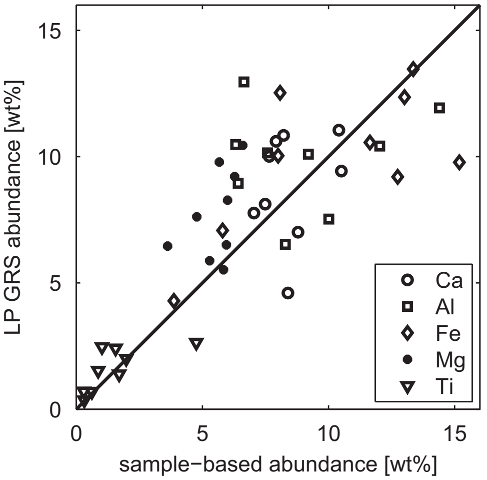

Fig. 1. LP GRS vs. sample-based elemental abundances for the Apollo and Luna landing sites, where sample-based bulk compositions are taken according to Elphic et al. (2000).

2.2. The Clementine UVVIS+NIR multispectral data set

The Clementine UVVIS+NIR multispectral data set contains pixel-synchronous lunar global mosaics at 415, 750, 900, 950, 1000, 1100, 1250, 1500, 2000, 2600, and 2780 nm with a lateral resolution of up to 100 m per pixel. The five UVVIS bands between 415 and 1000 nm were made publicly available by Eliason et al. (1999). By the year 1999, calibration of the NIR global mosaic spectral reflectance data set was sufficiently accurate between 1100 and 2000 nm to enable first qualitative studies of lunar mineral composition using a combined UVVIS+NIR data set (LeMouélic et al., 1999, 2000). Calibrated spectral reflectance lunar images from the Clementine UVVIS+NIR data sets are now available on the planetary data system (http://www.mapaplanet.org) and cover the wavelength range from 415 to 2000 nm. Calibration for the last two NIR at bands at 2600 and 2780 nm is generally thought to be less reliable.

3. UVVIS+NIR spectral features and their relation to mineral composition

Information about the identity of iron bearing (mafic) minerals (orthopyroxenes and clinopyroxenes) is contained in the band