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A normalisation framework for (hyper-)spectral imagery

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ABSTRACT

It is well known that the topography has an influence on the observed reflectance spectra. This influence is not compensated by spectral ratios, i.e. the effect is wavelength dependent. In this work, we present a complete normalisation framework.

The surface temperature is estimated based on the measured surface reflectance. To normalise the spectral reflectance with respect to a standard illumination geometry, spatially varying reflectance parameters are estimated based on a non-linear reflectance model. The reflectance parameter estimation has one free parameter, i.e. a low-pass function, which sets the scale of the spatial-variance, i.e. the lateral resolution of the reflectance parameter maps. Since the local surface topography has a major influence on the measured reflectance, often neglected shading information is extracted from the spectral imagery and an existing topography model is refined to image resolution.

All methods are demonstrated on the Moon Mineralogy Mapper dataset. Additionally, two empirical methods are introduced that deal with observed systematic reflectance changes in co-registered images acquired at different phase angles. These effects, however, may also be caused by the sensor temperature, due to its correlation with the phase angle.

Surface temperatures above 300 K are detected and are very similar to a reference method. The proposed method, however, seems more robust in case of absorptions visible in the reflectance spectrum near 2000 nm. By introducing a low-pass into the computation of the reflectance parameters, the reflectance behaviour of the surfaces may be derived at different scales. This allows for an iterative refinement of the local surface topography using shape from shading and the computation reflectance parameters. The inferred parameters are derived from all available co-registered images and do not show significant influence of the local surface topography. The results of the empirical correction show that both proposed methods greatly reduce the influence of different phase angles or sensor temperatures.

1. Introduction

Spectral measurements have emerged as standard methods in remote sensing. The information gained by (hyper-)spectral images ranges from shading to the local albedo and spectral absorptions. It is thus possible to derive the mineralogical and to some extent the elemental composition of the surface from spectral measurements. Additionally, the shading provides information on the local surface topography. Section 1.1 provides an overview on the possible information gained by (hyper-)spectral imagery. Since the measured spectral reflectance highly depends on the illumination conditions, a normalisation is required as described in Section 1.2. This study provides a complete normalisation framework as specified in Section 1.3.

1.1. Lunar (hyper-)spectral imagery

The earth's moon has been of scientific interest for a long time and thus a wealth of measurements, especially orbital measurements covering nearly the global lunar surface, exists and is publicly available. These measurements include (but are not limited to) high resolution topographic models derived from stereo analysis and laser altimetry, (hyper-)spectral reflectance measurements and elemental abundances measured by gamma ray spectrometers. Furthermore, there are physically motivated models describing the reflectance properties of the lunar surface (Shkuratov et al. 1999a,b; Hapke 1981, 1984, 1986, 2002). The lunar surface is thus an ideal target for the development of methods.

According to Shkuratov et al. (2011), optical measurements of the lunar surface can be sub-divided into three categories: phase photometry, spectrophotometry and polarimetry.

Polarimetry aims at the derivation of physical object properties based on the polarisation properties of the reflected light. Since it is of no importance to this thesis, the dedicated reader may refer to Shkuratov et al. (2011) for information on polarimetry.

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Phase photometry deals with reflectance measurements at the same wavelength range but different illumination conditions, i.e. different incidence, emission and phase angles. Consequently, the reflectance behaviour, i.e. the observed reflectance under different illumination conditions, of the lunar surface has been studied and models were developed. The most prominent models are those by Hapke (1981) and Shkuratov et al. (1999a). Since the incidence and emission angles change with the local topography of the lunar surface, the change in reflectance, i.e. the shading, provides clues on the local topography. Consequently, it is possible to recover the shape of the lunar surface from the shading observed in reflectance images as proposed by van Diggelen (1951), Wildey (1975), Horn (1975) and Kirk (1987).

Spectrophotometry analyses the spectral reflectance to derive the composition of the lunar surface material with respect to the minerals and chemical elements contained in it. The main minerals of the lunar surface are pyroxenes, plagioclase feldspars, olivines and ilmenite (Heiken et al., 1991). The bright highland material is predominated by the plagioclase feldspars, which were mainly identified based on their brightness (Shkuratov et al., 2011). The other minerals compose the dark maria regions. Due to transitions of the element iron, Fe^{2+} to be precise, these minerals exhibit crystal field absorption bands at characteristic wavelengths (Burns, 1993). Cloutis and Gaffey (1993) present laboratory spectra of lunar analogue minerals in the range 300–2600 nm of plagioclase (absorption band near 1300 nm), ilmenite (no band visible), pyroxenes (bands near 930 nm and near 1950 nm) and olivine (triple band resulting in a broad absorption band near 1050 nm). Similarly, McCord et al. (1972) present telescope-based measurements of lunar mare, highland, and bright crater areas. Burns et al. (1972) and Adams (1974) show that different pyroxenes may be distinguished by the position of the absorption bands. These spectral absorptions have been used to identify minerals in telescope-based reflectance spectra and later orbiter-based reflectance measurements. The identified components include impact melt (e.g. Smrekar and Pieters, 1985), spinel (e.g. Cloutis et al., 2004) and hydroxyl (e.g. Pieters et al., 2009b). Charette et al. (1974) quantified the absorptions using ratios of images at characteristic wavelengths, and showed that the wavelength ratio images are correlated to the titanium dioxide content. Mapping the titanium content has been continued by Melendrez et al. (1994) using telescope data and Lucey et al. (1998) using the Clementine orbiter multispectral imagery. In addition to titanium dioxide, Lucey et al. (1995, 1998, 2000) estimate the iron oxide content based on wavelength ratios. Later Shkuratov et al. (2005a) and Wöhler et al. (2011) proposed different approaches to map the spectral reflectance onto elemental abundance values measured by a gamma ray spectrometer.

1.2. Motivation

It is well known that the topography has an influence on the observed reflectance spectra. This influence is not compensated by spectral ratios, i.e. the effect is wavelength dependent. It was noted by Robinson and Jolliff (2002) that the shaded walls of lunar craters contained anomalously high percent of weight (wt%) elemental Iron (Fe) abundance estimates. The effect increased towards the lunar poles, where the northern or southern crater wall is always shaded. Robinson and Jolliff (2002) quantified that the iron oxide (FeO) and titanium dioxide (TiO_2) abundance maps derived from Clementine data showed an absolute difference of as much as 5 percentage of weight (FeO) and 4 percentage of weight (TiO_2) on 30° slopes. The strength of the effect varies over shaded and Sun-facing areas, however, it is stronger on shaded areas.

Additionally, the assumption of global parameters of the reflectance model leads to the selection problem as mentioned by Hillier et al. (1999). Due to the typical nadir-view of orbiter cameras, the phase angle equals the incidence angle and thus measurements acquired at higher phase angles typically correspond to surface areas of higher selenographic latitude. Consequently, different measurements along the range of phase angles most likely represent surface materials of different mineralogical compositions.

To compensate the aforementioned effects, a topographic model, preferably of better lateral resolution than the image data, and methods to estimate spatially varying parameters of the reflectance model are required. The estimation of local reflectance properties and high resolution topographic models is the target of photometric methods, e.g. photoclinometry (Kirk et al., 2003) and shape from shading (Horn, 1990). Using the shading variations along the lateral coordinate axes, the inclination of the surface and thus its gradient field may be retrieved from reflectance measurements.

This study aims at the combination of photometric shading and spectral information, i.e. the information along the lateral coordinate axes and the information along the spectral direction, by using the photometric methods by Grumpe et al. (2014) and Grumpe and Wöhler (2014) to extract the topography and the reflectance model that is necessary for the normalisation of the spectral data. The coupled estimation of topography and reflectance parameters obtains a self-consistent solution with spatially varying reflectance model parameters.

1.3. Contribution

In this study, we propose a complete framework for the normalisation of (hyper-)spectral data. This includes the estimation and the compensation of the thermal emission component based on the measured reflectance. The corrected reflectance is then normalised to standard viewing and illumination geometry with respect to spatially varying reflectance properties of the surface. This is achieved by an integrated approach that iteratively estimated the surface reflectance properties and refines existing topography models to image resolution using shape from shading. The whole framework is applied to the Moon Mineralogy Mapper (M^3) dataset and evaluated in comparison to published reference methods. Since the M^3 is known to be influenced by the sensor temperature (Besse et al., 2013b; Lundeen et al., 2011), an optional correction step is introduced.

1.4. Outline

At first, Section 2 presents an overview over recent (hyper-) spectral imagery, calibration and normalisation of spectral data and commonly used models of the thermal emission spectrum and the reflectance of the lunar surface. Section 3 then introduces the methods proposed in this study. The results obtained by the proposed methods are detailed in Section 4 and compared to other published methods. Finally, Section 5 summarises the content of this paper.

2. Related work

In general, spectral sensors measure a value, the so-called sensor counts, which is a possibly non-linear function of the radiance reflected from a target object into the sensor. To derive the reflectance, the sensor values require a conversion, the so-called radiance calibration. The reflectance, however, highly depends on the observation geometry, i.e. the orientation of the local topography of the object surface, the direction to the Sun and the direction to the observer. A normalised reflectance is thus computed by the so-called photometric normalisation or photometric correction.

At first, an overview on the recent instruments measuring the lunar reflectance and the lunar topography is given in Section 2.1. The calibration and the normalisation of the datasets are then described in Sections 2.3 and 2.4, respectively. The measured radiance is composed