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Construction of lunar DEMs based on reflectance modelling

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Abstract

Existing lunar DEMs obtained based on laser altimetry or photogrammetric image analysis are characterised by high large-scale accuracies while their lateral resolution is strongly limited by noise or interpolation artifacts. In contrast, image-based photometric surface reconstruction approaches reveal small-scale surface detail but become inaccurate on large spatial scales. The framework proposed in this study therefore combines photometric image information of high lateral resolution and DEM data of comparably low lateral resolution in order to obtain DEMs of high lateral resolution which are also accurate on large spatial scales. Our first approach combines an extended photoclinometry scheme and a shape from shading based method. A novel variational surface reconstruction method further increases the lateral resolution of the DEM such that it reaches that of the underlying images. We employ the Hapke IMSA and AMSA reflectance models with two different formulations of the single-particle scattering function, such that the single-scattering albedo of the surface particles and optionally the asymmetry parameter of the single-particle scattering function can be estimated pixel-wise. As our DEM construction methods require co-registered images, an illumination-independent image registration scheme is developed. An evaluation of our framework based on synthetic image data yields an average elevation accuracy of the constructed DEMs of better than 20 m as long as the correct reflectance model is assumed. When comparing our DEMs to LOLA single track data, absolute elevation accuracies around 30 m are obtained for test regions that cover an elevation range of several thousands of metres. The proposed illumination-independent image registration method yields subpixel accuracy even in the presence of 3D perspective distortions. The pixel-wise reflectance parameters estimated simultaneously with the DEM reflect compositional contrasts between different surface units. Specifically, the detected variations of the parameter of the single-particle scattering function indicate small-scale variations of the regolith particle size, possibly as a result of differences in soil maturity.

Keywords: DEM construction; Photoclinometry; Shape from shading; Reflectance modelling; Image registration

1. Introduction

The reconstruction of 3D surfaces based on 2D images has been of scientific interest for decades. However, most of the work is based solely on images while little work has been done on the fusion of photometric information, e.g. images, and absolute depth data, e.g. active range scanning, which has become available for a broad range of applications. We present an approach to reconstruct a 3D surface model, a so-called digital elevation model (DEM), from photometric measurements combined with absolute depth data of lower lateral resolution and synchronous estimation of the reflectance model. The result is a DEM which has the same lateral resolution as the image and the a vertical accuracy comparable to that of the absolute depth data. The algorithm is applied to regions of the lunar surface. This section motivates the proposed approach especially in the field of planetary DEM construction, presents a brief overview over related works throughout the literature, and introduces the dataset.

1.1. Motivation

Since planetary bodies tend to be large, remotely obtained data are important for the global understanding

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of a planet. Field sampling, e.g. core samples and laboratory measurements, are not feasible due to the large size of the investigated bodies. Thus, spatially comprehensive samples may only be acquired remotely. Furthermore, extraterrestrial planetary bodies simply are too far away for field samples. Within remote sensing, imagery is of high interest as it allows remote sampling of large areas at high lateral resolution. Applications range from high-resolution photographs, which are used for photogeologic interpretation of the surface structure, to hyperspectral imagery where images are taken across broad wavelength intervals. The latter technique is used to derive the reflectance behaviour of the surface at a large number of distinct wavelengths and infer the mineral composition of the surface (Mustard and Pieters, 1989).

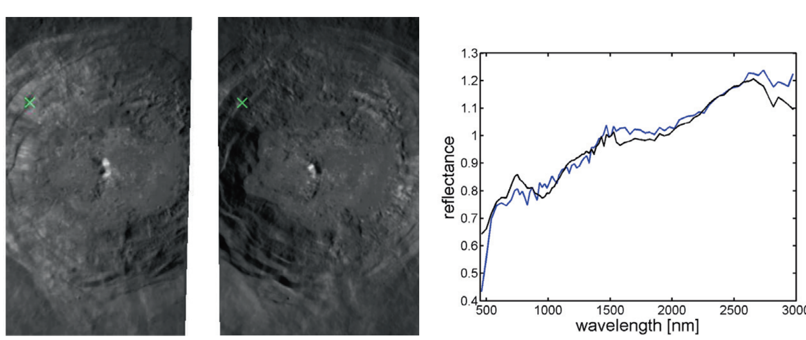
However, the measured spectral radiance and thus the spectral reflectance highly depend on the surface topography. This is illustrated in Fig. 1 which shows the spectral reflectance of the same surface area when the surface is illuminated by the sun from the east (blue) and from the west (black). The area of interest is located on the eastern side of a crater rim and thus shaded and brightened, respectively. To avoid misinterpretations of this distortion, the reflectance has to be normalised with respect to local topography.

Such a normalisation procedure requires a DEM which is co-registered with the image and has at least the same lateral resolution. Since the reflectance depends on the surface inclination, a DEM of two or three times the lateral image resolution would be preferable. However, in the case of the Moon no available DEM, including the gridded Lunar Orbiter Laser Altimeter (LOLA) DEM and the GLD100 which are introduced in detail in Section 1.4, globally matches the lateral resolution of modern hyperspectral data. In order to increase the lateral resolution of existing DEMs, we developed an approach to fuse the photometric information of the hyperspectral imagery with the absolute depth data of the available DEMs. The resulting refined DEM has the same lateral resolution as the images.

Besides the surface slope, the spectral reflectance depends on local surface properties, such as grain size and albedo, which may be wavelength dependent and therefore lead to a wavelength dependence of the parameters of the reflectance function. Hence, the resulting spectral reflectance may exhibit distortions (cf. Fig. 1(c)), such that the integrated estimation of surface topography and surface properties becomes inevitable. The spectral reflectance is thus normalised with respect to the surface topography and the local parameters of the reflectance function. Although the reconstruction of the surface topography can be based on a single channel of a multispectral or hyperspectral image sensor, the reflectance parameter estimation has to be applied to each channel separately, resulting in a pixel-wise spectrum of reflectance parameters.

1.2. Terminology

In this paper, the terms "photoclinometry" (PHCL) and "shape from shading" (SfS) are used frequently. Both terms are often considered as synonyms, denoting the recovery of topography from intensity or shading information, e.g. reflectance, in images. Historically, the term photoclinometry originates from planetary science while shape from shading was developed in the machine vision community. There are, however, a couple of differences within both methods. Here, we follow the reasoning of Horn (1990).



(a) Surface area illuminated from eastern direction (reflectance image at 1579 nm). Grey value range: 0–0.1. Image credit: NASA/JPL-Caltech

(b) Surface area illuminated from western direction (reflectance image at 1579 nm). Grey value range: 0–0.1. Image credit: NASA/JPL-Caltech

(c) Reflectance Spectra for both images at the location marked in green normalised to the reflectance at 1579 nm. The image illuminated from the east (blue line) shows an decreased absorption wavelength of the absorption trough near 1000 nm.

Fig. 1. Influence of the illumination geometry on the reflectance spectrum. (a) and (b) show the same surface area illuminated from different directions. (c) Two reflectance spectra corresponding to the pixel marked by a green x-mark. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)