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An advanced photogrammetric method to measure surface roughness: Application to volcanic terrains in the Piton de la Fournaise, Reunion Island

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ABSTRACT

We present a rapid in situ photogrammetric method to characterize surface roughness by taking overlapping photographs of a scene. The method uses a single digital camera to create a high-resolution digital terrain model (pixel size of ~1.32 mm) by means of a free open-source stereovision software. It is based on an auto-calibration process, which calculates the 3D geometry of the images, and an efficient multi-image correlation algorithm. The method is successfully applied to four different volcanic surfaces—namely, a′a lava flows, pahoehoe lava flows, slabby pahoehoe lava flows, and lapilli deposits. These surfaces were sampled in the Piton de la Fournaise volcano (Reunion Island) in October, 2011, and displayed various terrain roughnesses. Our in situ measurements allow deriving digital terrain models that reproduce the millimeter-scale height variations of the surfaces over about 12 m^2. Five parameters characterizing surface topography are derived along unidirectional profiles: the root-mean-square height (ξ), the correlation length (L_c), the ratio $Z_s = \xi^2/L_c$, the tortuosity index (τ), and the fractal dimension (D). Anisotropy in the surface roughness has been first investigated using 1-m-long profiles circularly arranged around a central point. The results show that L_c, Z_s and D effectively catch preferential directions in the structure of bare surfaces. Secondly, we studied the variation of these parameters as a function of the profile length by drawing random profiles from 1 to 12 m in length. We verified that ξ and L_c increase with the profile length and, therefore, are not appropriate to characterize surface roughness variation. We conclude that Z_s and D are better suited to extract roughness information for multiple eruptive terrains with complex surface texture.

1. Introduction

Surface roughness is a key factor in understanding soil and terrain properties in micrometeorology, agriculture, hydrology, and volcanology, as well as in planetary sciences. For instance, on cultivated fields it is an excellent indicator of soil sensitivity to wind erosion; it governs infiltration and runoff processes, and water storage; it influences incident radiation distribution and, indirectly, moisture, temperature, and aeration of the soil. This plays an important role in gas exchange and the development of soil biota (e.g., Vidal Vázquez et al., 2005). On weathered rock surfaces it is a measure of fragmentation mechanisms and thermal properties of surfaces (e.g., Tatone & Grasselli, 2009).

Together with the dielectric constant (equivalent of the complex refractive index) of materials and the terrain slope, surface roughness also controls scattering or emission of electromagnetic waves (Beckmann & Spizzichino, 1987). Its characterization is consequently critical to interpret optical and microwave remote sensing images from both terrestrial and planetary surfaces. However, in situ measurement of surface roughness on a distance of some meters remains a challenge due to the necessity to deploy a substantial geophysical setup.

Several contact (roller chain, pin profilometer) and noncontact (laser profilometer, terrestrial laser scanner, stereophotogrammetry) techniques have been applied to describe surface microrelief. Many authors have already related how to implement these techniques: the reader is referred to the review paper of Verhoest et al. (2008) for more details.

Contact techniques, such as pin profilometers, are difficult to handle and use, and their resolution is limited both in vertical and horizontal directions (e.g., Dexter, 1977; García Moreno et al., 2008). Moreover, they may alter the microtopography of the soil surface. A laser profilometer consists of a laser which moves along a horizontal

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rail and measures the distance to the surface. Single linear profiles, each from 1 to 5 m long, can be acquired in one passage (e.g., Bertuzzi et al., 1990a; Blaes & Defourny, 2008; Davidson et al., 2000; Vidal Vázquez et al., 2005). It is an accurate instrument, though constrained by its bulkiness, power consumption, and high cost of acquisition and operation. Both profilometers produce one-dimensional profiles that are not suited to characterize the 3D structure of natural surfaces. Multiplying the number of profiles along parallel transects would allow producing a two-dimensional grid and bypassing this limitation, but, in practice, applying this method outdoors is tedious.

Recently, techniques based on close-range stereophotogrammetry have proved their capacity to extract digital terrain models (DTM) with sub-millimeter accuracies (Chandler et al., 2005). Such DTMs have the advantage of providing a large number of profiles over large areas in one measurement only (Aguilar et al., 2009; Blaes & Defourny, 2008; Zribi et al., 2000). However, they require careful positioning and orientation of the cameras with respect to the surface, the use of bulky poles, and vertical calibration to minimize perspective distortion due to the focal length of the camera. Shadow analysis, which only requires taking one photograph at a solar angle of about 45°, has been also tested, but it seems to only work on light, uniformly-colored surfaces (García Moreno et al., 2008).

The last, and newest, category of instruments, is ground laser scanners which are particularly well suited for representing microtopography compared to the other techniques (Eitel et al., 2011; Haubrock et al., 2009). They are field-portable and the scanned surfaces can reach 100 m^2. However, the setup and calibration of these devices is more complex than all the other methods mentioned before. Comparative studies between different techniques have been performed: stereophotogrammetry and laser profilometer produce very similar height profiles (Aguilar et al., 2009; Blaes & Defourny, 2008); the same is true with shadow analysis versus pin profilometer (García Moreno et al., 2008).

As a summary, most of these techniques are difficult to use, especially in harsh volcanic terrains, and none of them is fully satisfactory in terms of cost, applicability or spatial sampling. Recently, substantial progress has been made in the generation of digital terrain models, such as in the reconstruction of urban architectural scenes, using several photographic images taken by off-the-shelf digital cameras positioned at different locations around the target. This technique has become a valuable tool in the reconstruction of high spatial resolution topographic surfaces, with a resolution ranging from a fraction of a millimeter (close-range photogrammetry) to a few centimeters (airborne photogrammetry).

This article presents a new method to characterize surface roughness and the results obtained when applied to different types of lava flows (a′a and pahoehoe) and lapilli. We first describe the photogrammetric processing chain and the DTM generation algorithm. Then we summarize the data set acquired in Reunion Island (France) in October, 2011. Finally we calculate five parameters generally used to describe surface roughness characteristics for a variety of lava flows and discuss an example of the implication of our measurements for the monitoring of ground deformations by remote sensing, as well as for planetary surface studies.

2. Materials and methods

2.1. Generating high-resolution surface models

Stereophotogrammetry has long been the simplest method to calculate the three-dimensional coordinates of points on an object using stereo 2D image pairs (Egelsn & Kasser, 2001). In the last two decades, the tremendous development of cost-effective, high-quality digital cameras and the exponential increase in computing power have led to very active research in the fields of photogrammetry and computer vision. There are several commercial and open-source software packages, like Photosynth (Microsoft Live Labs/University of Washington) or PMVS (*Patch-based Multi-view Stereo Software*), which identify common points on multi-view digital images and generate a three-dimensional model of the photographed object. Such tools have been successfully used to reconstruct realistic object models for several applications. The reconstructed scenes are generally consistent with visual perception. Despite impressive results, they lack mathematical rigor in the formulation of the equations, which leads to low accuracy for scientific applications. Geomorphologists and civil engineers increasingly need affordable, light, but also accurate tools to study the relief of natural scenes or to survey buildings (Pierrot-Deseilligny et al., 2011).

In this context, in 2007, the Institut national de l'information géographique et forestière (IGN) has developed a set of free, open-source, multi-view stereo software packages labeled Apero-MicMac (*Aérotriangulation Photogrammétrique Expérimentale Relativement Opérationnelle — Multi-Images Correspondances, Méthodes Automatiques de Corrélation*), which generate 3D models out of images taken from arbitrary positions. In short Apero-MicMac uses a set of images and camera parameters, such as the focal length and the pixel size, to create a depth map of the scene which in turn is converted into a 3D point cloud. Detailed information on this tool is available at (http://logiciels.ign.fr/?Telechargement,20). Hereafter we will briefly describe the parallel shooting mode implemented in this study. Apero-MicMac consists of three modules:

i) The first module, a key step of unoriented image coregistration, selects all the pairs of images and searches those in which tie-points (vertex and corners of objects characterized by high gradients) are present. A scale-invariant feature transform (SIFT) is applied to extract local features in optical images (Lowe, 2004). The SIFT method is invariant to image scaling, translation and rotation, and partly invariant to illumination and 3D viewpoint changes. These properties make it a good candidate for analyzing relatively flat terrains such as bare soils.

ii) The second module, called Apero, automatically computes the relative orientation of the images. First they are oriented one after the other relative to a master image. The order of priority is given by the number and distribution of the tie-points extracted by the first module. Then all initial orientations are iteratively adjusted at the same time. Other sources of information like GPS measurements, ground control points, reference objects, etc. may be used at this stage. The main challenge is to choose a good initial guess for the relative orientations. A poor estimate of this configuration is a common cause of failure. The way the data are acquired is therefore crucial: spending more time in the field during the experiment can save substantial effort in post-processing the data.

iii) MicMac, the third module, starts from the optimal orientations calculated by Apero. It consists in producing an accurate and dense depth map of the scene. A depth map contains distance information of all points of the scene that are seen from a viewpoint. It can be converted into a 3D point cloud, which is generated by means of an energy minimization algorithm. The cost function is the sum of two terms: one that accounts for the correlation between areas of the images and the other that accounts for the smoothness of the reconstructed 3D surface (local gradient). The minimization problem is solved by a multiscale dynamic programming algorithm, with a pyramidal structure for the computation. This algorithm takes advantage of the redundancy of the images (each point is actually seen by 10 images). MicMac computes the DTM in a Euclidean space, so the result is a grid where $z = f(x,y)$. It is well adapted to “flat” scenes and has the advantage of storing the result in a single depth map.

Apero-MicMac is definitely more complex to use compared to other open source sofwares but, in return, it is more complete and