# 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 & Spizichino, 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 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; Davidson et al., 2000; Vidal Vázquez et al., 2005; Blaes & Defourny, 2008). 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 (Zribi et al., 2000; Blaes & Defourny, 2008; Aguilar et al., 2009). 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 (Haubrock et al., 2009; Eitel et al., 2011). They are field-portable and the scanned surfaces can reach 100 m2. 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 (Blaes & Defourny, 2008; Aguilar et al., 2009); 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.

# 1. Materials and methods

# *1.1. 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 (Egels & 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 . 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 accurate. Pierrot-Deseilligny & Cléry (2011, 2012) describe protocols adapted to architectural studies; however it has never been applied to bare soils or rocks to extract information on surface roughness. A first attempt is described in the following sections. Modeling the small-scale topography of lava flows is, a priori, simpler than doing it on a bas-relief: one only needs to mimic the flight plan of an aircraft taking successive strips of regularly spaced vertical photos (parallel shooting mode). To ensure the connection between two images, adjacent images should ideally overlap by at least 60% but since this protocol is difficult to implement in the field with hand-held photos, a large oversampling is recommended.

# *1.2. Survey data set*

The Piton de la Fournaise volcano, Reunion Island (France) is a typical basaltic shield volcano. It is considered as one the world's most active volcano, with frequent but short-lived eruptions and a major one occurring in April 2007. The temporal and geographical variability of the lava flows and lapilli, associated with successive eruptive events, leads to complex surface geomorphology and texture. They generate substantial ambiguities when assessing the interferometric synthetic aperture radar (InSAR) phase coherence, and consequently make the quantitative monitoring of surface deformation particularly difficult. While the assessment of surface geomorphology can be addressed using airborne images, limitations in assessing properly surface roughness compromise the development of lava flow models, which results in a poor understanding of the eruptive history, and hence, a failure to address the magma budget in the magma chamber.

To address this lack of information about surface roughness, we investigated fourteen spots during a geophysical survey set up in late October, 2011, at the Piton de la Fournaise volcano (Table 1). They correspond to four types of volcanic terrain that display various surface roughnesses: pahoehoe and a'a lava flows located in the Grand Brûlé (GB, average elevation ~100 m) and the Enclos Fouqué (ENC, average elevation ~2270 m); and slabby pahoehoe flows and smooth lapilli deposits located in the Plaine des Sables (PDS, average elevation ~2290 m).

Table 1. Distribution of the fourteen spots. The site names point out the area: Grand Brûlé (GB), Plaine des Sables (PDS), and Enclos Fouqué (ENC).

|  |  |  |  |
| --- | --- | --- | --- |
| **Surface** | **Grand Brûlé** | **Plaine des Sables** | **Enclos Fouqué** |
| Lapilli |  | PDS1813, PDS2021, PDS2102 |  |
| Slabby pahoehoe lava flows |  | PDS1927, PDS2135, PDS3043 |  |
| Pahoehoe lava flows | GB3215, GB3247 |  | ENC2683, ENC2798 |
| a'a lava flows | GB3114, GB3332 |  | ENC2597, ENC2698 |

Variations in the surface roughness of the volcanic materials provide important information about the mode of emplacement (viscosity, flow and cooling rate, etc.) as well as the erosional processes. Pahoehoe lava flows are generally characterized by a smooth, ropy or even bumpy surface, while a'a lava flows display a fragmentary, spinose surface with irregularly shaped vesicles. Slabby pahoehoe flows contain a series of closely spaced slabs, a few meters across and a few centimeters thick, broken and tilted by mass movement of the underlying lava. They seem to plow up the lapilli deposits which are ubiquitous in the Plaine des Sables.

The photos have been captured by hand at a distance of ~1.8 m above ground using a commercial 18 megapixel digital camera, a Canon EOS 60D, and stored in RAW format to retain as much information as possible. The acquisition protocol consists in acquiring successive images along parallel strips − all shots are more or less oriented in the same direction − while handling the optical axis of the digital camera approximately perpendicular to the ground surface (Figure 1).

|  |
| --- |
| P1040601.jpg |
| **Figure 1.** Shooting protocol over a recent a'a lava flow in the Enclos Fouqué (ENC2597). |

In order to build a pattern of multiple stereo images, we ensured that our lateral and transversal overlapping rates were at least 70%. The focal length was set to 18 mm so that, on average, each image covers an area of 1.71 m × 1.14 m. The area of the spots ranged from 5.9 m2 to 24.6 m2 and the number of images varied from 30 to 78 (Figure 2). A reference tape measure was used to estimate the scaling factor. The length of the tape measure and the corresponding pixel coordinates in a stereoscopic pair are introduced in the orientation module described in section 2. This scaling factor allows us to produce an accurate DTM.

|  |
| --- |
| **10 cm** |
| **Figure 2. Principle of the method**. The background represents the digital terrain model of a pahoehoe lava flow (ENC2798) and the pyramids the camera fields of view, as computed by MicMac. |

In total, thirteen over the fourteen spots are studied (Figure 3). For each of them, a sub-millimeter DTM has been generated. Originally the pixel size was ranging between 0.31 mm and 0.35 mm at full resolution, according to the DTM, but we divided it by four to obtain 1.24-1.40 mm in order to decrease the size of the files. As for the vertical resolution, it has been evaluated at 0.61-0.70 mm. These values are the same order of magnitude compared to similar studies (Verhoest et al., 2008) and accurate enough for our application.

|  |  |
| --- | --- |
| Image1(a) | Image2(b) |
| Image3(c) | |
| Image4(d) | Image5(e) |
| **Figure 3.** Digital terrain models of (a) bumpy pahoehoe lava flow (GB3247), (b) ropy pahoehoe lava flows (ENC2798), (c) slabby pahoehoe lava flow (PDS1927), (d) a'a lava flow (ENC2698), and (e) lapilli deposits (PDS1851). Note the reference tape measure at the top of subplot (e). | |

The method of characterizing surface roughness relies on 1D profiles that can be extracted from these surfaces by applying the Bresenham line algorithm (Bresenham, 1965). This algorithm determines which points should be selected in the regular grid DTM model to form a straight line; it is commonly used to draw lines on a computer screen. Detrending, i.e., subtraction of a best-fit line from the data, allows us to remove the influence of the local slope and to study the microrelief around a horizontal reference level. For the surfaces studied here, a visual inspection of the data suggested a best fit with a linear trend line for most profiles. Alternative methods like polynomial fits or moving average algorithms are also used to remove slope effect or low frequencies in the topographic signal. Therefore, each profile can be described by a function expressed by  where  is the horizontal reference axis in the direction of the profile and  is the height of the points related to this axis. It is notable that the mean level  equals zero after detrending. We also verified that the height distribution function constructed from most of the DTMs had a Gaussian shape, although the behavior of some surfaces tend to depart from an ideal bell curve.

Given the very high resolution of the DTM, surface roughness characterization of the fourteen sites was carried out in two ways:

1) We extracted directional profiles to characterize roughness anisotropy. In each spot, we selected circular zones 1 m in diameter. These discs have approximately the same size as the footprint of the airborne LiDAR data that have been acquired over the volcano in 2008 and 2009. Then 180 1 m linear profiles have been extracted for every degree between 1° and 180° with regard to a reference direction. Note that the pixels that are close to the center of the circle may belong to several directions.

2) Linear profiles from 1 to 12 m have been randomly extracted over the sites. As an example, Figure 4 shows four profiles measured over four different surfaces along a 4 m transect. A quick visual inspection of these profiles is enough to recognize and separate the a'a lava flow (roughest surface), the pahoehoe lave flow (bumpy and ropy surface), and the lapilli (smoothest surface). Indeed, the a'a lava flow shows the highest elevation amplitude (of the order of ~15 cm) whereas the lapilli deposits seem to be very flat. Ropy and bumpy pahoehoe lava flows are geometrically similar and present an intermediate degree of roughness.

|  |
| --- |
|  |
| **Figure 4.** DTM profiles of a'a (ENC2698) lava flows, 'bumpy' (GB3247) and 'ropy' (ENC2798) pahoehoe lava flows, and lapilli deposits (PDS1851). |

# *1.3. Surface statistics*

Roughness can be defined as a measure of the topographic relief of a surface (Bennett & Mattsson, 1999). Several parameters can be calculated along linear profiles to describe roughness in each volcanic terrain type. There are currently no standard methods for quantitatively characterizing surface roughness (Shepard et al., 2001). In this paper only the parameters the most commonly reported by the remote sensing community are studied. The root-mean-square (standard deviation) height  of a profile is simply calculated according to:

|  |  |
| --- | --- |
|  | (1) |

where  is the height of the profile at position  and  the number of sample points. The higher , the more important the vertical variations of the surface. However, this parameter does not take into account horizontal structures and therefore incompletely characterizes surface roughness.

The autocorrelation function  expresses the correlation of paired sample measurements as a function of the distance between samples. For discrete values, the autocorrelation may be obtained as:

|  |  |
| --- | --- |
|  | (2) |

where **** is the root-mean-square height and  represents the average of the  pairs of points separated by a distance .  ranges between −1 and +1 and, by definition, it is maximum for the value of the lag length of 0. It tends to decrease when  increases. The correlation length of the profile  is then the value of  at which  drops to  of its value at zero lag:

|  |  |
| --- | --- |
|  | (3) |

The higher , the lower the horizontal variations of the surface. Zribi & Dechambre (2002) noticed that in many studies, the effect of  on the radar backscattering coefficient was neglected and that only  was inverted, leading to large errors in the estimation of surface roughness. In order to mix the effects of these two parameters, they proposed a unique parameter called **** and defined as:

|  |  |
| --- | --- |
|  | (4) |

The ratio  is presented by these authors as a slope effect. As seen earlier, a smooth surface corresponds to a small value of  and a large value of , and thus to a small , and vice versa. The tortuosity index is another parameter that accounts for both the horizontal and vertical scales of the roughness (Bertuzzi et al., 1990b). It is defined as:

|  |  |
| --- | --- |
|  | (5) |

where  is the actual length of the profile and  its projected horizontal length.  increases with the degree of surface roughness. This index that implies no theoretical assumptions is easy to compute.

Finally, the auto-similarity of the surface can be quantified by means of the fractal dimension, which has been reported to be a discriminative parameter to characterize ground types (e.g., Pachevsky et al., 1997; Franceschetti et al., 2000; Shepard et al., 2001; Vidal-Vazquez et al., 2005). The number of methods which can be used to determine the fractal dimension of one-dimensional profiles is relatively large (e.g., box-counting, R/S, variogram, maximum entropy). They provide variable results depending on the fractal model, so that they are difficult to compare. Moreover, there is still a range of contrasting opinions regarding the choice of one method over another (Klinkenberg, 1994). We applied the roughness-length method published by Malinverno (1990); it consists in computing average values of root-mean-square heights for different scale ranges :

|  |  |
| --- | --- |
|  | (6) |

where  is the total number of windows of length ,  is the number of points within the ith window ,  are the residuals on the trend, and  is the mean residual. We estimated the linear trend within each window using least-squares regression so that the mean residual is zero. It also explains the  degrees of freedom used to calculate the root-mean-square roughness. As suggested by Malinverno (1990), we let  vary between the shortest span containing at least 10 points and 20% of the total length of the profile. Adjacent windows were allowed to overlap by 50% along the profile and, at each step, the window length was decremented by a factor of 0.9. As a result  increases with the windows length  as follows:

|  |  |
| --- | --- |
|  | (7) |

where  is a constant and  is a scaling parameter called the Hurst exponent . If we plot  as a function of , we obtain a straight line.  is consequently measured from the slope of the log-log plot of  versus . For a linear profile, it is related to the fractal dimension  by  . Note that Gallant et al. (1994) tested this method on synthetic fractal profiles and used the maximum length of the profile for the higher value of . Following them, however, led to a deterioration of the results.  is a powerful measure of the change in surface roughness as a function of the measurement scale: a large value indicates that the surface gets smooth rapidly as the scale increases, whereas a small value implies that the surface tends to maintain its roughness. For , the surface is said self-similar, i.e., its roughness is constant at any scale (Shepard et al., 2001).

# 2. Results

*2.1. Anisotropy of surface roughness*

Due to the difficulty to reconstruct DTM with high accuracy, surface roughness anisotropy has been predominantly applied to geomaterials, like rock and concrete (e.g., Baker et al., 2008; Tatone & Grasselli, 2009). Only few studies deal with natural or agricultural soils (Blaes & Defourny, 2008). The computed roughness parameters can be visualized in a polar coordinate system where the direction of each line gives the angle at which the profile is taken with regard to a reference direction, and the distance from the origin corresponds to the parameter value for that orientation. Although these graphs are complex to interpret, the study of the 14 sites shows various anisotropy behaviors. Consider the lapilli deposits in the Plaine des Sables (Figure 5a): they do not display any visible directional feature. Now consider one of the ropy pahoehoe lava flows investigated in the Enclos Fouqué, on the west of the Dolomieu crater (Figure 5b). Several apparent structures are present in the DTM. In particular, the direction in which the lava flows goes from right to left, with a direction change in the middle of the image. The latter consequently displays two main flow directions, at about 10° and 150° with regard to the reference direction (horizontal line). We expect roughness to be higher in these two directions due to the ropy appearance of the lava flow.

|  |  |
| --- | --- |
|  |  |
| **Figure 5.** Zoom on the DTM of two volcanic terrains displaying different surface roughness features: (a) lapilli deposits (PDS2021) and (b) ropy pahoehoe lava flow (ENC2683). The red circles are ~1 m in diameter. The two white lines on the left plot represent the main directions in which the lava flows, at about 10° and 150° (or −30°) with regard to the horizontal direction. | |

Figure 6 illustrates the angular variation of the five roughness parameters calculated over the two surfaces. The angles vary from 1° to 180° counterclockwise. Because quantifying isotropy is a ticklish issue, the following analysis will principally rely on a visual examination of the shape of the polar plots. Roughness parameter values that are nearly equal in all directions produce a roughly circular plot, while those that display one or several distinct oriented lobes result in elliptical or sinusoidal-shaped plots.

As expected, the lapilli deposits behave like an isotropic surface. The rose diagrams of all the parameters except **** do not display any clear angular dependency showing preferential directions. As far as the fractal dimension  is concerned, the spatial dispersion around the mean value is statistically indiscernible. The scattering properties of electromagnetic waves by this surface may not change when rotating it about its normal.

In contrast, on the ropy pahoehoe basalt lava flow, the **** parameter rose diagram displays two main lobes centered on the two main flow directions, 10° and 150°, while the rose diagrams of the correlation length  and the fractal dimension  are oriented towards the long axes of the corrugations that are perpendicular to the direction of flow. Although such surface structures are quantitatively limited in extent, they are very distinctive and a textbook case to study surface roughness (Fink & Flechter, 1978). The root-mean-square height  and the tortuosity index  do not allow us to accurately identify these directions. In conclusion, , **** and  seem to be the most appropriate parameters to describe directional surface roughness.

|  |  |
| --- | --- |
| **Root-mean-square height**  **(cm)** | |
| RosePlot_StdVsDir_Iso | RosePlot_StdVsDir_Aniso |
| **Correlation length  (cm)** | |
| RosePlot_LcVsDir_Iso | RosePlot_LcVsDir_Aniso |
| **parameter (cm)** | |
| RosePlot_ZsVsDir_Iso | RosePlot_ZsVsDir_Aniso |
| **Tortuosity index** | |
| RosePlot_TauVsDir_Iso | RosePlot_TauVsDir_Aniso |
| **Fractal dimension** | |
| RosePlot_DFVsDir_Iso | RosePlot_DFVsDir_Aniso |
| **Figure 6.** Roughness parameters calculated on the DTM of two sites: PDS2021 (left) and ENC2683 (right). The outer circle gives the maximum value and the inner one the average value. The black lines on the right plots represent the preferential directions at 10° and 150° (see Figure 5b). | |

The mean and standard deviation of the five roughness parameters, calculated for 60 circular spots selected at random over the different volcanic terrains, are gathered in Table 2. The vertical component of roughness is well quantified by the root-mean-square height: the values confirm what we know intuitively, namely that the a'a lava flows are rougher than the pahoehoe and slabby lava flows, whereas the lapilli deposits are very flat ****. The higher values observed on the a'a lava flows **** are due to their typical fragmented or blocky surfaces. The variations of  are high for the four terrain types (, with  the dispersion of ). On the other hand, the correlation length is not very discriminating since the pahoehoe lava flows show higher values than lapilli, although the latter are smoother ****. Moreover, **** does not change a lot **** and we observe a high variability (in the order of 30%). The **** parameter and the tortuosity index, which accounts for both the vertical and horizontal components, follow the same trend as . The **** parameter varies by a factor of 10 from one type of surface to another **** whereas  is only multiplied by two ****. Therefore, in spite of high dispersion values (****, with  the dispersion of ), the **** parameter appears to be a good candidate for measuring surface roughness. Finally the fractal dimension moves in the opposite direction to the root-mean-square height and the **** parameter: the rougher the surface, the lower the fractal dimension ****. This parameter is very stable for each terrain type (, with  the dispersion of ). It ranges from 1.21 for the a'a lava flows to 1.74 for the lapilli: the latter are considered as smooth at the higher scales, even if at smaller scales, one perceives them as being smooth, and both the a'a and pahoehoe lava flows are statistically rough. The high standard deviation of the parameters may be explained by the short profile length and by the anisotropic behavior of the surfaces.

Table 2. Roughness characteristics (root-mean-square height , correlation length ,  parameter, tortuosity index , and fractal dimension ) calculated for  circular spots selected over several volcanic terrains.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Surface** |  | **Parameter** | **(cm)** | **(cm)** | **(cm)** |  |  |
| Lapilli | 11 | Minimum | 0.19 | 3.47 | 0.01 | 1.07 | 1.63 |
| Maximum | 0.47 | 15.49 | 0.03 | 1.15 | 1.80 |
| Mean | 0.25 | 7.30 | 0.01 | 1.11 | 1.74 |
| Standard deviation | 0.09 | 3.35 | 0.01 | 0.04 | 0.07 |
| Median | 0.24 | 7.19 | 0.01 | 1.12 | 1.75 |
| Interquartile range | 0.07 | 3.32 | 0.01 | 0.07 | 0.13 |
| Slabby pahoehoe lava flows | 14 | Minimum | 0.91 | 5.74 | 0.12 | 1.16 | 1.21 |
| Maximum | 3.04 | 12.36 | 1.30 | 1.80 | 1.60 |
| Mean | 1.80 | 7.80 | 0.57 | 1.43 | 1.37 |
| Standard deviation | 0.76 | 1.68 | 0.39 | 0.23 | 0.11 |
| Median | 1.59 | 8.00 | 0.49 | 1.35 | 1.35 |
| Interquartile range | 1.43 | 1.55 | 0.74 | 0.31 | 0.18 |
| Pahoehoe lava flows | 20 | Minimum | 0.98 | 4.64 | 0.14 | 1.19 | 1.12 |
| Maximum | 4.37 | 13.76 | 1.46 | 1.59 | 1.50 |
| Mean | 2.20 | 9.56 | 0.62 | 1.34 | 1.27 |
| Standard deviation | 1.04 | 3.05 | 0.40 | 0.13 | 0.10 |
| Median | 2.02 | 9.22 | 0.59 | 1.31 | 1.27 |
| Interquartile range | 1.63 | 5.15 | 0.54 | 0.18 | 0.11 |
| a'a lava flows | 15 | Minimum | 3.19 | 5.23 | 1.59 | 1.67 | 1.16 |
| Maximum | 6.39 | 11.56 | 4.67 | 2.29 | 1.30 |
| Mean | 4.73 | 8.28 | 3.08 | 2.02 | 1.21 |
| Standard deviation | 1.03 | 1.98 | 0.97 | 0.24 | 0.04 |
| Median | 4.87 | 8.15 | 2.96 | 2.13 | 1.21 |
| Interquartile range | 1.52 | 3.30 | 2.01 | 0.49 | 0.07 |

These results meet the hierarchy given by Mazzarini et al. (2007) where the a'a lava flows are the roughest, followed by the pahoehoe lava flows and the lapilli. The roughness parameters of the slabby pahoehoe lava flows are often close to those of the ordinary pahoehoe lava flows, but they do not necessarily vary in the same direction compared to the other surfaces, so that it is difficult to determine which of the two surfaces is the roughest. For instance,  and  seem to demonstrate that the slabby pahoehoe lava flows are smoother than the pahoehoe lava flows, while  shows the contrary.

*2.2. Effect of profile length on roughness parameters*

The results obtained using random profiles of variable effective horizontal length **** are gathered in Table 3 and illustrated by Figure 7. A first comparison of Table 2 and Table 3 shows that the mean and standard deviation calculated for **** are very similar. If the fourteen spots could easily provide us with 1 m to 5–6 m long profiles, the longest one that reaches 12 m could only be extracted on the most elongated spot that corresponds to a slabby pahoehoe lava flow. Quantifying the effect of the profile length on the roughness parameters is challenging due to the statistical variability of these parameters. To answer that question, Oh & Kay (1998) generated randomly rough surfaces using Monte Carlo simulations: they showed that to estimate the root-mean-square height  and the correlation length **** with a precision of ±10%, the profile length **** should at least equal  and , respectively. Therefore conventional profilometers that acquire 1 or 2 m long profile data may be not adapted to study such parameters experimentally. Some field measurements have been performed using a 25 m long laser profilometer by Davidson et al. (2000) over agricultural soils near Toulouse (France) and Matera (Italy), and by Baghdadi et al. (2000) over volcanic terrains in the Afar rift (Republic of Djibouti). These authors report that  and **** first exponentially increase with the profile length, for all types of surfaces, before saturating for ****and ****, respectively. We observe a linear increase but no saturation (Figs 7a & 7b). On the contrary, the other three parameters, namely the  parameter (Fig. 7c), the tortuosity index **** (Fig. 7d), and the fractal dimension **** (Fig. 7e)do not significantly vary as a function of the profile length ****. Campbell & Shepard (1996), who studied the roughness of the Kilauea Volcano terrains (Hawai'i, USA), found that **** covered a wide range of values (1.32–1.56) on various pahoehoe lava flows, compatible with our observations, and that **** on a'a lava flows, a value that seems to be largely overestimated compared to our observations. To sum up, these three statistical criteria that clearly distinguish the different surfaces and are insensible to **** provide a powerful measure of the change in surface roughness. We also observe a high dispersion of , **** and , whereas **** and **** show low variations for each surface type ( and ). The standards deviations of  and **** seem to increase with the degree of roughness and the profile length (Figs 7a & 7b), whereas the dispersion of  decreases with the profile length and increases with the degree of roughness (Figs 7c).

Table 3. Mean and standard deviation of the roughness parameters (root-mean-square height , correlation length ,  parameter, tortuosity index , and fractal dimension ) for several volcanic terrains as a function of the profile length .  is the number of sites. In each site, 50 profiles have been drawn at random, except for those that exceed 6 m and for which 20 profiles are available.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Surface** | **(m)** |  | **(cm)** | **(cm)** | **(cm)** |  |  |
| Lapilli | 1 | 4 | 0.23 ± 0.04 | 5.44 ± 1.31 | 0.02 ± 0.02 | 1.12 ± 0.06 | 1.73 ± 0.05 |
| 2 | 4 | 0.31 ± 0.08 | 14.32 ± 1.97 | 0.01 ± 0.01 | 1.11 ± 0.06 | 1.74 ± 0.04 |
| 3 | 4 | 0.45 ± 0.15 | 26.58 ± 7.75 | 0.01 ± 0.01 | 1.11 ± 0.05 | 1.74 ± 0.05 |
| 4 | 4 | 0.65 ± 0.22 | 43.31 ± 8.19 | 0.01 ± 0.01 | 1.11 ± 0.06 | 1.74 ± 0.05 |
| 5 | 1 | 1.10 ± 0.00 | 60.87 ± 0.00 | 0.02 ± 0.00 | 1.12 ± 0.00 | 1.78 ± 0.00 |
| 6 | 1 | 1.60 ± 0.00 | 73.76 ± 0.00 | 0.03 ± 0.00 | 1.12 ± 0.00 | 1.78 ± 0.00 |
| Slabby pahoehoe lava flows | 1 | 3 | 1.90 ± 0.63 | 7.19 ± 1.56 | 0.67 ± 0.37 | 1.46 ± 0.21 | 1.33 ± 0.07 |
| 2 | 3 | 2.69 ± 0.79 | 13.47 ± 1.90 | 0.68 ± 0.34 | 1.48 ± 0.21 | 1.35 ± 0.03 |
| 3 | 3 | 3.16 ± 1.12 | 19.55 ± 2.59 | 0.65 ± 0.38 | 1.47 ± 0.23 | 1.35 ± 0.05 |
| 4 | 3 | 3.67 ± 1.37 | 26.43 ± 5.33 | 0.66 ± 0.42 | 1.49 ± 0.22 | 1.36 ± 0.05 |
| 5 | 2 | 3.32 ± 0.83 | 27.56 ± 10.08 | 0.56 ± 0.47 | 1.49 ± 0.30 | 1.35 ± 0.06 |
| 6 | 2 | 3.59 ± 0.99 | 34.17 ± 14.87 | 0.55 ± 0.49 | 1.49 ± 0.31 | 1.36 ± 0.06 |
| 7 | 2 | 5.28 ± 3.36 | 54.90 ± 15.41 | 0.58 ± 0.54 | 1.40 ± 0.20 | 1.35 ± 0.05 |
| 8 | 2 | 5.48 ± 3.19 | 65.80 ± 19.39 | 0.50 ± 0.41 | 1.35 ± 0.10 | 1.35 ± 0.07 |
| 9 | 2 | 5.96 ± 3.11 | 78.89 ± 27.69 | 0.48 ± 0.32 | 1.39 ± 0.15 | 1.37 ± 0.04 |
| 10 | 2 | 6.46 ± 2.66 | 88.70 ± 23.24 | 0.48 ± 0.27 | 1.37 ± 0.08 | 1.38 ± 0.05 |
| 11 | 2 | 7.13 ± 1.92 | 105.10 ± 20.85 | 0.49 ± 0.17 | 1.37 ± 0.07 | 1.38 ± 0.05 |
| 12 | 1 | 7.24 ± 0.00 | 101.64 ± 0.00 | 0.52 ± 0.00 | 1.32 ± 0.00 | 1.40 ± 0.00 |
| Pahoehoe lava flows | 1 | 4 | 1.84 ± 0.20 | 8.02 ± 1.27 | 0.53 ± 0.03 | 1.36 ± 0.11 | 1.29 ± 0.08 |
| 2 | 4 | 2.72 ± 0.60 | 14.82 ± 1.48 | 0.61 ± 0.20 | 1.37 ± 0.04 | 1.30 ± 0.08 |
| 3 | 4 | 3.67 ± 0.71 | 24.62 ± 0.55 | 0.64 ± 0.22 | 1.36 ± 0.06 | 1.30 ± 0.08 |
| 4 | 3 | 4.61 ± 0.41 | 30.57 ± 1.08 | 0.82 ± 0.15 | 1.36 ± 0.06 | 1.28 ± 0.06 |
| 5 | 3 | 4.74 ± 0.89 | 36.30 ± 7.71 | 0.69 ± 0.17 | 1.37 ± 0.05 | 1.28 ± 0.08 |
| a'a lava flows | 1 | 4 | 4.81 ± 0.83 | 7.29 ± 0.72 | 3.61 ± 1.22 | 2.08 ± 0.28 | 1.22 ± 0.02 |
| 2 | 4 | 6.03 ± 0.98 | 11.05 ± 2.04 | 3.98 ± 1.42 | 2.09 ± 0.34 | 1.23 ± 0.04 |
| 3 | 4 | 6.67 ± 1.16 | 16.41 ± 6.26 | 3.47 ± 1.35 | 2.05 ± 0.31 | 1.25 ± 0.05 |
| 4 | 4 | 7.46 ± 1.10 | 20.15 ± 9.24 | 3.72 ± 1.54 | 2.11 ± 0.31 | 1.26 ± 0.05 |
| 5 | 1 | 8.48 ± 0.00 | 42.01 ± 0.00 | 2.05 ± 0.00 | 1.74 ± 0.00 | 1.24 ± 0.00 |

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
| **Figure 7.** Evolution of (a) the root-mean-square height , (b) the correlation length , (c) the  parameter, (d) the tortuosity index , and (e) the fractal dimension  as a function of the profile length. | |

# Conclusion

We applied an efficient photogrammetric method to generate local digital terrain models using a commercial digital camera. Following a simple acquisition protocol, the processing chain MicMac proved to be a relevant tool to generate extremely dense DTM (millimeter ground resolution). As a free open source solution, it can be easily tested and implemented in several applications. It simplifies the use of close range photogrammetry and should initiate new research areas in Earth or planetary sciences, such as surface change detection, geomorphology, energy balance, erosion, and others.

Based on these DTMs, we were able to study roughness over surfaces ranging from 6 m2 to 25 m2. Several roughness parameters have been examined over four different types of ground surfaces in the area of the Piton de la Fournaise volcano. Such a local investigation is crucial for assessing surface roughness over large-scale areas using remote-sensing data. In particular, it will improve InSAR monitoring of pre-eruptive phase in active terrains. Our results suggest that the **** parameter introduced by Zribi & Dechambre (2002), the tortuosity index ****, and the fractal dimension ****, allow discriminating between volcanic terrains displaying a wide range of surface conditions. Nevertheless, only **** and **** provide additional information about the directional behavior of surface roughness. In agriculture, soils surfaces may be highly anisotropic, according to the tillage practices; thus, directional roughness analysis may be very useful.

In the future, these properties will be used to invert the radar backscattering coefficients using empirical models (e.g., Campbell & Shepard, 1996; Dierking, 1999; Zribi & Dechambre, 2002; Campbell, 2009). They will be also helpful to map volcanic products, such as lava flows with a smoother or rougher aspect, or lapilli deposits using LiDAR data (e.g., Mazzarini et al., 2007; Favalli et al., 2009).

They could be relevant parameters to classify complex textures, such as volcanic areas, and possibly, with further investigations using LiDAR and SAR backscattering properties, be linked with geological properties of materials such as the age of lava flows. In the future, these surface roughness parameters will be used as inputs for electromagnetic models to predict the backscattering coefficient.

Finally, on planetary terrain where surface roughness is largely defined by cratering and volcanic processes, landing sites selection, rover trafficability, as well as human extravehicular activities, is largely defined by the ability to accurately measure terrain roughness. The above-described method will enable the optimization of the surface trajectories for scientific data acquisition (Deans et al., 2012), which will maximize the number of the explored sites per trajectory. In addition, the production of local ground-level DTM at centimeter or even millimeter scale will greatly optimize sample collection and drilling activities for in-situ rovers.

**Acknowledgments**

This work was funded by the CNES Terre Océan Surfaces Continentales Atmosphère (TOSCA) program in the frame of the DEVOIR (*DEformation of active vegetated VOlcanos using Insar and lidaR*) project. E. Heggy and M. Arab-Sedze were also supported by the DESDynI (*Deformation, Ecosystem Structure and Dynamics of Ice*) team. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. We thank our colleagues from the Observatoire Volcanologique du Piton de la Fournaise (IPGP) for their support during the geophysical survey and M. Dechambre (LATMOS) for the fruitful discussions about roughness. This paper is an IPGP contribution number 3379.

# References

Aguilar, M. A., Aguilar, F. J., & Negreiros, J. (2009). Off-the-shelf laser scanning and close-range digital photogrammetry for measuring agricultural soils microrelief, *Biosystems Engineering*, *103*, 504−517.

Baghdadi, N., Paillou, P., Grandjean, G., Dubois, P., & Davidson, M. (2000). Relationship between profile length and roughness variables for natural surfaces, *International Journal of Remote Sensing*, *21*, 3375-3381.

Baker, B. R., Gessner, K., Holden, E. J., & Squelch, A. P. (2008). Automatic detection of anisotropic features on rock surfaces, *Geosphere*, *4*, 418−428.

Beckmann, P., & Spizzichino, A. (1987). *The scattering of electromagnetic waves from rough surfaces*, Artech House, 503 pp.

Bennett, J. M., & Mattsson, L. (1999). *Introduction to surface roughness and scattering*, Optical Society of America, 130 pp.

Bertuzzi, P., Caussignac, J. M., Stengel, P., & Morel, G. (1990a). An automated, noncontact laser profile meter for measuring soil roughness *in situ*, *Soil Science*, *149*, 169−178.

Bertuzzi, P., Rauws, G., & Courault, D. (1990b). Testing roughness indices to estimate soil surface roughness changes due to simulated rainfall, *Soil & Tillage Research*, *17*, 87−99.

Blaes, X., & Defourny, P. (2008). Characterizing bidimensional roughness of agricultural soil surfaces for SAR modeling, *IEEE Transactions on Geoscience and Remote Sensing*, *46*, 4050−4061.

Bresenham, J. E. (1965). Algorithm for computer control of a digital plotter, *IBM Systems Journal*, 4, 25−30.

Campbell, B. A., & Shepard, M. K. (1996). Lava flow surface roughness and depolarized radar scattering, *Journal of Geophysical Research*, *101*, 18,941−18,951.

Campbell, B. A. (2009). Scale-dependent surface roughness behavior and its impact on empirical models for radar backscatter, *IEEE Transactions on Geoscience and Remote Sensing*, *47*, 3480−3488.

Chandler, J. H., Fryer, J. G., & Jack, A. (2005). Metric capabilities of low-cost digital cameras for close range surface measurement, *The Photogrammetric Record*, *20*, 12–26.

Davidson, M. W. J., Le Toan, T., Mattia, F., Satalino, G., Manninen, T., & Borgeaud, M. (2000). On the characterization of agricultural soil roughness for radar remote sensing studies, *IEEE Transactions on Geoscience and Remote Sensing*, *38*, 630−640.

Deans, M. C., Fong, T., Pedersen, L., Utz, H., Nefian, A., & Edwards, L. (2012). Advanced robotic surface navigation for Mars exploration, in *Proc. Workshop on Concepts and Approaches for Mars Exploration*, 12-14 June 2012, Houston, Texas. LPI Contribution No. 1679.

Dexter, A. R. (1977). Effect of rainfall on the surface micro-relief of tilled soil, *Journal of Terramechanics*, *14*, 11−22.

Dierking, W. (1999). Quantitative roughness characterization of geological surfaces and implications for radar signature analysis, *IEEE Transactions on Geoscience and Remote Sensing*, *37*, 2397−2412.

Eitel, J. U. H., Williams, C. J., Vierling, L. A., Al-Hamdan, O. Z., & Pierson, F. B. (2011). Suitability of terrestrial laser scanning for studying surface roughness effects on concentrated flow erosion processes in rangelands, *Catena*, *87*, 398−407.

Egelsn Y., & Kasser M. (2001). *Digital Photogrammetry*, CRC Press, 376 pp.

Favalli, M., Fornaciai, A., & Pareschi, M. T. (2009). LIDAR strip adjustment: Application to volcanic areas, *Geomorphology*, *111*, 123−135.

Fink, J. H., & Fletcher, R. C. (1978). Ropy pahoehoe: surface folding of a viscous fluid, *Journal of Volcanology and Geothermal Research*, 4, 151−170.

Franceschetti, G., Iodice, A., Maddaluno, S., & Riccio, D. (2000). A fractal-based theoretical framework for retrieval of surface parameters from electromagnetic backscattering data, *IEEE Transactions on Geoscience and Remote Sensing*, *38*, 641−650.

Gallant, J. C., Moore, I. D., Hutchinson, M. F., & Gessler, P. (1994). Estimating fractal dimension of profiles: a comparison of methods, *Mathematical Geology*, *26*, 455−481.

García Moreno, R., Saa Requejo, A., Tarquis Alonso, A. M., Barrington, S., & Díaz, M. C. (2008). Shadow analysis: a method for measuring soil surface roughness, *Geoderma*, *146*, 201−208.

Haubrock, S. N., Kuhnert, M., Chabrillat, S., Güntner, A., & Kaufmann, H. (2009). Spatiotemporal variations of soil surface roughness from in-situ laser scanning, *Catena*, *79*, 128−139.

Klinkenberg, B. (1994). Review of methods used to determine the fractal dimension of linear features, *Mathematical Geology*, *26*, 23−46.

Lowe, D. G. (2004). Distinctive image features from scale-invariant keypoints, *International Journal of Computer Vision*, *60*, 91−110.

Malinverno A. (1990). A simple method to estimate the fractal dimension of a self‐affine series, *Geophysical Research Letters*, *17*, 1953−1956.

Mazzarini, F., Pareschi, M. T., Favalli, M., Isola, I., Tarquini, S., & Boschi, E. (2007). Lava flow identification and aging by means of lidar intensity: Mount Etna case, *Journal of Geophysical Research*, *112*, B02201.

Oh, Y., & Kay, Y. (1998). Condition for precise measurement of soil surface roughness, *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 691−695.

Pachevsky, Y. A., Ritchie, J. C., & Gimenez, D. (1997). Fractal modeling of airborne laser altimetry data, *Remote Sensing of Environment*, *61*, 150−161.

Pierrot-Deseilligny, M., & Clery, I. (2011). Apero, an open source bundle adjustment software for automatic calibration and orientation of set of images, *Proceedings of the ISPRS Commission V Symposium, Image Engineering and Vision Metrology*, Trento, Italy, 2-4 March 2011, 8 pp.

Pierrot-Deseilligny, M., De Luca, L., & Remondino, F. (2011). Automated image-based procedures for accurate artifacts 3D modeling and orthoimage generation, *23th Int. CIPA Symposium*, Prague, Czech Republic, 12-19 September 2011.

Pierrot-Deseilligny, M., & Clery, I. (2012). Some possible protocols of acquisition for the optimal use of the "Apero" open source software in automatic orientation and calibration, *EuroCow 2012*, Barcelona, Spain, 8-10 February 2012, 10 pp.

Shepard, M. K., Campbell, B. A.,Bulmer, M. H., Farr, T. G., Gaddis, L. G., & Plaut, J. J. (2001). The roughness of natural terrain: a planetary and remote sensing perspective, *Journal of Geophysical Research*, *106*, 32777−32795.

Tatone, B. S. A., & Grasselli, G. (2009). A method to evaluate the three-dimensional roughness of fracture surfaces in brittle geomaterials, *Review of Scientific Instruments*, *80*, 125110.

Verhoest, N. E. C., Lievens, H., Wagner, W., Álvarez-Mozos, J., Moran, M. S., & Mattia, F. (2008). On the soil roughness parameterization problem in soil moisture retrieval of bare surfaces from synthetic aperture radar, *Sensors*, *8*, 4213−4248.

Vidal Vázquez, E., Vivas Miranda, J. G., & Paz González, A. (2005). Characterizing anisotropy and heterogeneity of soil surface microtopography using fractal models, *Ecological Modelling*, *182*, 337−353.

Zribi, M., Ciarletti, V., Taconet, O., Boissard, P., Chapron, M., & Rabin, B. (2000). Backscattering on soil structure described by plane facets, *International Journal of Remote Sensing*, *21*, 137−153.

Zribi, M., & Dechambre, M. (2002). A new empirical model to retrieve soil moisture and roughness from C-band radar data, *Remote Sensing of Environment*, *84*, 42−52.