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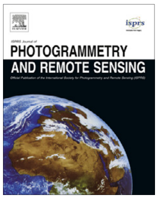

# Roughness measurements over an agricultural soil surface with Structure from Motion

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ABSTRACT

This paper presents an accessible and reliable method to measure surface roughness of agricultural soils with a setup designed to tackle some of the challenges posed by roughness to SAR remote sensing. The method relies on Structure from Motion (SfM). From a large collection of unconstrained images (~700 images) acquired with a commercial-grade camera, digital elevation models (DEMs) are generated for a SAR-pixel-size plot (2 × 11 m), with horizontal and vertical RMS errors of respectively 1.5 mm and 3.1 mm.

Example results highlight the need for individually detrending all sampled sub-DEMs when studying the convergence of the roughness parameters for increasing DEM length. This point appears to be missing in previous publications. The efficiency of the Fourier-based method used to compute the roughness parameters allows investigating anisotropy at a 1° angular resolution. This could benefit investigations on the *flashing fields* phenomenon observed within narrow direction bands over tilled fields.

The inclusion of permanent reference targets into the soil makes multitemporal measurements over the same plot straightforward. Ten acquisitions from April to July 2013 show noticeable natural changes in roughness with cracking during dry periods and smoothing during rainfalls. As expected, changes in RMS height and correlation length appear inversely correlated and can be related to in situ measurements of soil moisture, soil temperature, and rainfall. Analysis of changes in power spectral density indicates that the observed roughness changes only affect scales below 50 cm, *i.e.* scales relevant for microwave scattering. Even though it seems that millimetric changes for horizontal scales below 1 cm are not observable, measurement performance could be improved by adding more detailed pictures to the image set.

This SfM-based method appears to be well-suited to study the dynamics and characterization of roughness for SAR and more generally for geosciences.

## 1. Introduction

When estimating soil moisture at field scale, surface roughness is known to affect radar signal as much as does soil moisture, so that the inverse problem cannot be resolved with only a single radar acquisition. This ambiguity moisture/roughness has been identified as the most challenging aspect of high resolution estimation of soil moisture (Barrett et al., 2009). In situ measurements of roughness can be used for development of backscattering models or for their validations, *i.e.* to study the forward problem, or to estimate soil moisture, *i.e.* to solve the inverse problem. From an operational perspective, in situ roughness measurements are usually not available to solve the inverse problem. In theory it is possible to remove the moisture/roughness ambiguity by combining images with different radar configurations (multi-polarized, multi-frequency, multi-incidence and/or multitemporal acquisition (Balenzano et al., 2011; Yang et al., 2006; Wickel et al., 2001; Gherboudj et al., 2011; Oh, 2004; Baghdadi et al., 2006)). Methods relying on multitemporal acquisitions assume that soil surface roughness remains roughly constant throughout a series of observations. At the moment there are no reliable observations to confirm this assumption. Knowledge about temporal roughness dynamics remains poor.

Surface roughness changes primarily because of tillage operations and weather conditions (rainfall, freeze/thaw) (Zobeck and Onstad, 1987). While tillage operations produce noticeable

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and relatively deterministic changes according to the tool used, natural changes especially from rainfalls are less easily traceable. Previous studies related to changes due to rainfall can be found mainly in soil erosion research which investigates rill network formation and soil transport (Moritani et al., 2011; Berger et al., 2010; Peter Heng et al., 2010; Rieke-Zapp and Nearing, 2005). Rainfall was found to produce a series of transformations starting from loose aggregates, to crust consolidation, and then rills formation. Exponential models were used to describe the decrease in roughness with the amount of rain. However, as these erosion studies rely on experiments with simulated storms (40 mm/h) or in tropical region (Guzha, 2004), with highly inclined soil surface (10°), applicability of these results to roughness changes due to light rainfall (a few mm of rain per hour) is arguable. In research related to radar remote sensing, very few analysis of natural changes in roughness are available. Callens et al. analyzed the effect of natural rainfall on their roughness measurements along transects which spanned almost over three months (Callens et al., 2006). They could detect a slight decrease in RMS height over a cultivated plot, while the rest of the measurements did not reflect any meaningful variations. Marzahn et al. also noticed a smoothing effect due to natural rainfall characterized by a decrease in RMS height and an increase in correlation length for some digital elevation models (DEMs) acquired 5 months apart (Marzahn et al., 2012). Álvarez-Mozos et al. analyzed changes in roughness parameters for 5 acquisition dates across 4 months, with measurements along transects (Álvarez-Mozos et al., 2009). The observed variations were rather erratic, without correlation between RMS height and correlation length. Eventually, there is no trace in the literature of analysis of a time series of robust roughness measurements systematically acquired over the same plot.

This lack of knowledge regarding roughness temporal dynamics partly originates from limitations of roughness measurement methods and limitations of the analysis tools.

Initially, roughness measurements were usually made along profiles of limited length with meshboards or pin profilers, which led to unreliable roughness statistic estimation. In particular RMS height and correlation length, commonly used in backscattering models, have been reported to vary with the transect length (Oh and Kay, 1998; Davidson et al., 2000; Callens et al., 2006). And these directional measurements can hardly capture roughness anisotropy (Marzahn et al., 2012; Blaes et al., 2004). Methods based on laser scanner/profiler or on stereo-photogrammetry have then been implemented to measure roughness parameters over 3D DEMs, and have improved spatial analysis of roughness. Today both methods can produce quality DEMs with accuracy of a few millimeters even in outdoor conditions. From a study based on ten 4 m long simulated profiles with added noise, Lievens et al. showed that a 2-mm uncertainty on the height measurements had negligible impacts on soil moisture estimation (Lievens et al., 2009). A higher robustness can be expected from 3D measurements because of the larger number of measurement points available (Marzahn et al., 2012). The main downside of laser scanners with millimeter accuracy over extended area and resilience to outdoor conditions, might be their cost. Stereo-photogrammetry is more affordable but has other limitations. In particular, it can be accurate only if special care is taken for the setup (camera calibration, sturdy stand for targets/cameras, accurate knowledge of external orientation) (Mirzaei et al., 2012). This required setup accuracy might also be difficult to achieved with muddy soils or windy conditions. Moreover, even though stereo-photogrammetry is becoming more accessible, post-processing still requires knowledge of photogrammetry. Therefore there is need for a more robust, systematic and accessible method to measure surface roughness.

In addition, while the latest photogrammetric setups allow generating DEMs over extended surface area, the same analysis tools are being used to estimate the roughness parameters. These tools are suitable for transects, but they lead to impracticable computational time when applied to high resolution DEMs. This is particularly true for the estimation of correlation length. This parameter is usually computed from the empirical semi-variogram over transects, but computing the semi-variogram for an entire DEM requires either under-sampling or focusing on reduced-size DEM (Blaes and Defourny, 2008; Marzahn et al., 2012).

The objective of this article is to present a powerful measurement process based on the Computer Vision method Structure from Motion (SfM) along with some example results. The example results are obtained with a computationally efficient method based on the Fourier transform of the DEM, which allows computing the roughness parameters without discarding any points of the DEM.

This new measurement method tackles the main limitations of laser scanners and stereo-photogrammetry. It is low-cost, does not require specific knowledge in photogrammetry, nor accurate setup calibration, and can cope with a variety of outdoor conditions. Even for large surface areas, it is accurate enough to be used for microwave scattering.

In Section 2, the requirements of the measurements are presented and the measurement setup is explained in detail. A description of the method used to compute the roughness parameters is also given. In Section 3, measurement performance is assessed for a 2 × 3.4 m DEM of an agricultural soil surface. Section 4 gives example results which are here to illustrate the possibilities offered by the presented method. Therefore there are no attempts at deriving conclusions from them. First the result section makes use of a single DEM (1) to compute roughness parameters for increasing DEM length, and (2) to show that SfM and the Fourier based analysis tools can capture non-obvious traces of anisotropy. Then a time series of DEMs demonstrates that meaningful changes in RMS height, correlation length and power spectral density can be detected over a short period time and under natural conditions. Finally, a discussion covers (1) the limitations of the method with some practical aspects, (2) its applicability to measuring other roughness scales, (3) its potential benefits for radar remote sensing, and (4) eventual other applications.

## 2. Materials and methods

This section presents first the driving requirements for the design of the measurement process, then broadly describes the measurement process. A more specific description of SfM and of the use of reference points is then given. The last subsection gives the theoretical details of the method used to estimate the roughness parameters.

### 2.1. Requirements and constraints

SfM is a very versatile technique for the generation of 3D numerical model from unconstrained 2D images. It requires many images of the surface, with reference points included to define the linear scale. The method described was developed for an agricultural test site near Cranfield University and can be applied quite generally for surface roughness measurements on a wide range of scales.

### 2.1.1. Measurement extent

At the moment, it is still not clear on which spatial scales surface roughness needs to be measured to account for its effects in backscattering models (Lievens et al., 2009). Manninen points that roughness statistics should ideally be characterized over a pixel-size surface (Manninen, 2003). Current spaceborne SAR instruments, such as RADATSAT-2 (Livingstone et al., 2006), can