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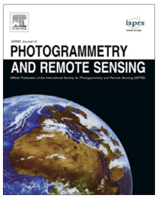

Correction of terrestrial LiDAR intensity channel using Oren–Nayar reflectance model: An application to lithological differentiation

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ABSTRACT

Ground-based LiDAR has been traditionally used for surveying purposes via 3D point clouds. In addition to *XYZ* coordinates, an intensity value is also recorded by LiDAR devices. The intensity of the backscattered signal can be a significant source of information for various applications in geosciences.

Previous attempts to account for the scattering of the laser signal are usually modelled using a perfect diffuse reflection. Nevertheless, experience on natural outcrops shows that rock surfaces do not behave as perfect diffuse reflectors. The geometry (or relief) of the scanned surfaces plays a major role in the recorded intensity values.

Our study proposes a new terrestrial LiDAR intensity correction, which takes into consideration the range, the incidence angle and the geometry of the scanned surfaces. The proposed correction equation combines the classical radar equation for LiDAR with the bidirectional reflectance distribution function of the Oren–Nayar model. It is based on the idea that the surface geometry can be modelled by a relief of multiple micro-facets. This model is constrained by only one tuning parameter: the standard deviation of the slope angle distribution (σ_{slope}) of micro-facets.

Firstly, a series of tests have been carried out in laboratory conditions on a 2 m^2 board covered by black/white matte paper (perfect diffuse reflector) and scanned at different ranges and incidence angles. Secondly, other tests were carried out on rock blocks of different lithologies and surface conditions. Those tests demonstrated that the non-perfect diffuse reflectance of rock surfaces can be practically handled by the proposed correction method.

Finally, the intensity correction method was applied to a real case study, with two scans of the carbonate rock outcrop of the Dents-du-Midi (Swiss Alps), to improve the lithological identification for geological mapping purposes. After correction, the intensity values are proportional to the intrinsic material reflectance and are independent from range, incidence angle and scanned surface geometry. The corrected intensity values significantly improve the material differentiation.

1. Introduction

Ground-based LiDAR or Terrestrial Laser Scanning (TLS) is commonly used to acquire 3D point clouds (*XYZ* coordinates) containing highly accurate and dense information about the surface topography (Slob and Hack, 2004). Besides the three-dimensional coordinates, most TLS devices record an additional attribute called "intensity" for each point of the point cloud. This attribute is mainly used to improve point cloud visualization. Currently, the LiDAR intensity channel is used, in several domains of geosciences, as a source of information about the surface properties. For instance, LiDAR intensity values can be used: in volcanology for delineation of lava flow events (Mazzarini, 2005); in land cover analysis for detection and classification of wetlands and vegetation or for biomass differentiation (Donoghue et al., 2007); in glaciology for albedo quantification of a given glacier surface (Joerg et al., 2015); in geoarcheology for locating the ruins (Challis et al., 2011). More specifically, several studies showed applications of LiDAR intensity to discriminate between rock types (Bellian et al., 2005; Buckley et al., 2010, 2008; Burton et al., 2011; Franceschi et al., 2011, 2009). In addition, Penasa et al. (2014) proposed an automatic segmentation method based on the intensity channel. Recent studies demonstrated the potential of ground-based LiDAR

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to enhance geological mapping on vertical outcrops, as shown by Matasci et al. (2015). Since the LiDAR intensity channel is increasingly used for various applications, a proper understanding and processing of LiDAR intensity values is a critical step to go further in the treatment and interpretation of 3D point clouds.

The intensity values recorded by TLS devices depend on several parameters. Some are related to the TLS device itself: laser beam wavelength, emission power, beam opening angle, system attenuation and internal calibration (e.g. Larsson et al., 2007). Others are related to the scanned surface: range (i.e. the distance from the TLS to the target), incidence angle (i.e. orientation of the surface relative to the laser beam), surface composition and moisture content (Feng et al., 2001; Jelalian, 1992; Jutzi and Gross, 2009; Kaasalainen et al., 2011; Reshetyuk, 2006; Schaer et al., 2007; Soudarissanane et al., 2011). Atmospheric conditions may also alter the path of the laser beam and reduce the intensity of the backscattered signal (Jelalian, 1992; Rüeger, 1996; Weichel, 1990). In order to be able to use intensity for lithological mapping, one should correct for all influences not related to the material composing the rock surface. This can be performed by applying a series of corrections to the backscattered intensity signal. Some correction models have already been proposed for multiple returns LiDAR (e.g. Ahokas et al., 2006; Höfle and Pfeifer, 2007; Kaasalainen et al., 2005). Other correction equations have also been published for single return ground-based LiDAR using empirical models, based on calibrated targets or fitted function (e.g. Li et al., 2013; Penasa et al., 2014; Pfeifer et al., 2008, 2007). Other approaches use range and incidence angle to correct LiDAR intensity (e.g. Franceschi et al., 2009; Vain and Kaasalaine, 2011). However, these corrections assume that target surfaces are perfect diffuse reflectors (i.e. Lambertian reflectors), which is not always valid in the case of natural rocky outcrops.

Indeed, based on the analysis of 3D point clouds of different outcrops composed of different lithologies, it has recently been observed that to consider rock surfaces as Lambertian reflectors to correct the intensity channel leads to an over-correction of the intensity values of high incidence angles (Humair et al., 2015; Matasci et al., 2015). This discrepancy between observations and results of the commonly used correction models may be related to the fact that numerous surfaces, especially in natural outcrops, do not behave as perfect diffuse reflectors following Lambert's cosine law (Nayar et al., 1991). Hence, the current challenge consists of providing a physically-based LiDAR intensity channel correction equation likely to take into account for the non-Lambertian behavior of natural rocky surfaces. This correction should be able to satisfactorily correct the intensity channel for the range, the incidence angle plus to take into consideration some material surface properties.

In this paper, we propose to combine a physical model based on the bidirectional reflectance distribution function (BRDF) with the standard radar equation described by Nicodemus et al. (1992) and Wagner (2010). The selected BRDF uses the physical background of basic light reflection developed in computer graphic by Nayar et al. (1991). The Oren–Nayar BRDF model takes into account the surface roughness of the target to compute the reflected luminance. To model the surface roughness of the target, the Oren–Nayar BRDF simulates the surface roughness as a series of micro-facets angled according a Gaussian distribution, oriented uniformly and acting as a perfect diffuse reflector (i.e. Lambertian reflector). The results showed that a distribution of perfect diffuse reflectors leads to non-Lambertian behavior. Moreover, the Oren–Nayar model allows the correction of Lambertian as well as non-Lambertian reflectors with a single adjustable parameter.

In order to demonstrate the efficiency of this new correction model for LiDAR intensity values, we applied it to different materials in various outcropping conditions. We first used an experimental set-up: a board covered by the matte paper acting as a near perfect diffuse reflector. Experiments were conducted varying the range from 10 to 1000 m and the incidence angle from 0° to 85°. The new correction model was applied to rock blocks with homogeneous lithologies, to illustrate the non-Lambertian reflection of rock bodies. Finally, we applied our correction to a real outcrop setting (the Dents-du-Midi, Switzerland) where TLS data were acquired from different locations in order to assess the efficiency of the correction equation when using multiple scans. The results show significant improvements for lithological differentiation when compared to uncorrected or classically corrected (i.e. using Lambert's cosine law) LiDAR intensity models. This opens up new perspectives for segmentation and mapping of rock types based on the intensity channel.

2. Theory

The intensity channel of LiDAR data is a numerical representation of the recorded backscattered signal power. It is provided in an arbitrary unit, unique to the specific LiDAR device and directly proportional to the recorded returned power. Its value depends on different physical parameters as mentioned above. Since both laser and radar electromagnetic waves follow the same principles, the well-known radar equation can be used to describe the main parameters affecting the received signal power (P_r). We use Wagner (2010)'s formulation of the radar equation which is valid for a laser beam with a width angle β_t and a circular detector of diameter D_r.

$$P_r = \frac{P_t D_r^2}{4\pi R^4 \beta_t^2} \eta_{sys} \eta_{atm} \sigma_{cross} \tag{1}$$

where P_t is the transmitted pulse power in watt; R is the range or distance from the scanner to the target in meters; β_t is the laser beam width in radians; D_r device receiver aperture in meter; η_{sys} is the system transmission efficiency for TLS optical components; η_{atm} is the atmospheric transmission factor, and σ_{cross} is the target cross-section in square meters.

Assuming that the target is larger than the laser beam and that its surface is a perfect diffuse reflector (i.e. Lambertian), the cross-section σ_{cross} is:

$$\sigma_{cross} = \pi \rho_\lambda R^2 \beta_t^2 \cos\alpha \tag{2}$$

where ρ_λ is the reflectivity of the surface for a defined wavelength λ; and α is the incidence angle (i.e. the angle between the incident beam and the normal to the surface).

By substituting σ_{cross} from Eq. (2) in Eq. (1), we get the simplified radar equation (3):

$$P_r = \frac{P_t D_r^2 \rho_\lambda \cos\alpha}{4R^2} \eta_{atm} \eta_{sys} \tag{3}$$

From Eq. (3), we can split the different parts into three main categories: the terms depending on instrumental (P_t, D_r, η_{sys}) and atmospheric factors (η_{atm}); the terms depending on scanning geometry (α, R); and the term depending on target material properties (ρ_λ).

2.1. Instrumental and atmospheric factors

LiDAR components experience oscillations due to vibrations and fluctuations caused by internal (i.e. warm-up) and external factors (e.g. ambient temperature, relative humidity), which ultimately cause perturbations in emitted and received signals and so on the recorded backscattered intensity (Larsson et al., 2007; Reshetyuk, 2006). As discussed in Höfle and Pfeifer (2007), the parameter η_{sys} is usually considered as a constant related to a given