Modeling hemispherical reflectance for natural surfaces based on terrestrial laser scanning backscattered intensity data

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Abstract: Independent of instrumental properties and scanning geometry, target reflectance is significantly important for terrestrial laser scanning (TLS) data processing and utilization, especially in multi-temporal and multi-sensor cases. In addition to the 3D topographic coordinates, TLS systems also record the backscattered intensity value of each point that provides additional information on the reflectance characteristics of the scanned surface. However, a number of confounding variables, particularly the distance and incidence angle, distort the ability of the original intensity to directly retrieve the target reflectance. This study proposes a new method to model the hemispherical reflectance of natural surfaces from the TLS intensity data by eliminating the effects of incidence angle and distance. The incidence angle effect is corrected by the Oren-Nayar reflectance model which takes individual surface roughness into account whereas the irregular distance effect is eliminated by reference targets without estimating the specific distance-intensity function. The Faro Focus120 terrestrial scanner is utilized in the case study. Six typical natural surfaces are chosen as the experimental objects. Results imply that the proposed method exhibits high accuracy in retrieving reflectance values. The deviation of the retrieved reflectance values from that measured by a spectrometer is approximately 4.29% and the root mean square error (RMSE) is approximately 0.0562.

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OCIS codes: (280.3640) Lidar; (290.5820) Scattering measurements; (290.5880) Scattering, rough surfaces.

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1. Introduction

Terrestrial laser scanning (TLS), a revolutionary technique for the acquisition and documentation of spatial data, allows a direct and illumination-independent measurement of objects in a fast, contactless, and non-invasive manner by emitting narrow beams of light mostly in the near-infrared region of the electromagnetic spectrum [1]. With high-density and high-accuracy point cloud, TLS can provide a detailed 3D representation of the scanned objects and has been widely used in a variety of applications in the past two decades [2]. Additionally, TLS is an active remote sensing technique. In addition to the 3D geometric information, TLS photodetector simultaneously records a radiometric measurement, i.e., the backscattered laser signal of each scanned point. The backscattered optical power is internally converted to a voltage, amplified in the system, and finally transformed into a Digital Number (DN), that is, a scaled integer value called “intensity” [3, 4].

Intensity, which is insensitive to ambient light and shadowing, is initially used to improve point cloud separability. Apart from visualization purposes, the intensity data can be used as a major or complementary data source in various object-based studies, such as point cloud classification and segmentation, vegetation and forest investigation, road traffic marking identification, water content extraction, and glacier albedo studying [5–8]. Also, intensity is
associated with the reflectance properties of the scanned surface and provides good spectral separability for detecting and classifying objects [5]. The term reflectance refers to the total fraction of the incident power on unit surface area scattered into upper hemisphere by unit area of surface in the laser wavelength [9–11]. Utilizing reflectance would facilitate the development of an automatic and accurate classification and feature extraction in the processing of TLS data. Theoretically, surfaces of higher reflectance will reflect a greater portion of the incident laser radiation, thereby increasing the backscattered (received) signal power and further the intensity [5]. However, the original intensity data are influenced by multiple variables and are unique to the specific instrument. Retrieving reflectance from intensity data becomes a challenge [4, 9].

Since the instrumental effect is kept constant during one campaign and the atmospheric attenuation can be ignored, the intensity data scanned by the same TLS sensor are predominately influenced by the target reflectance, distance, and incidence angle [12]. In order to utilize intensity for further applications, all influences not related to the material composing the scanned surface, i.e., the effects of incidence angle and distance, should be corrected [13]. Various studies have been successfully conducted to derive a relative corrected intensity that is merely related to the reflectance of the scanned target by correcting the incidence angle and distance effects [1, 5, 12–14]. These methods can be divided into: empirical models and theoretical models [3]. However, these existing methods have some limitations. Firstly, it is assumed that scanned surfaces are perfect diffuse reflectors (i.e., Lambertian). The Lambert’s cosine law is therefore extensively used to correct the incidence angle effect. However, natural surfaces do not behave as perfect Lambertian reflectors and Lambert’s cosine law can lead to an over-correction of the intensity values of high incidence angles [1, 7, 15]. Additionally, the TLS distance effect does not completely follow the inverse square range function from the radar range equation at near ranges [1, 14]. Moreover, a relative intensity value depends on the instrumental parameters and scanning geometry [13], which is far from enough in the direct comparison and combination of the data from multi-temporal and multi-sensor cases. Consequently, an absolute reflectance value is urgently needed [16, 17], particularly in the cases where TLS data are integrated with other data source, such as SAR and optical remote sensing imagery data. For multispectral light detection and ranging (LiDAR) systems, modeling an absolute reflectance is extremely important because some physical quantities (e.g., normalized difference vegetation index (NDVI)) can be derived by comparing the reflectance values at different wavelengths. The reflectance depends only on the target scattering properties and the laser wavelength [18–20]. Previous studies have indicated that the incidence angle effect is mainly caused by the target surface characteristics whereas the distance effect is dominated by instrumental effects [1, 13] and the incidence angle and distance effects can be solved separately. Based on the achievements of previous studies, we propose to retrieve an absolute reflectance by using a new method to correct both the incidence angle and distance effects in this study.

In our previous study, both the incidence angle and distance effects were empirically corrected by a polynomial to reconstruct the reflectance [20]. However, natural targets differ significantly with surface characteristics (e.g., surface roughness) and can only be approximated as Lambertian [21–23]. The polynomial parameters derived from Lambertian reflectors may not be suitable for natural surfaces, especially when the surface structures of a natural target differ significantly with that of a Lambertian. Therefore, parameters should be estimated individually and surface characteristics should be considered in the correction of the incidence angle effect. The Oren-Nayar reflectance model takes the target surface roughness into account to compute the reflected luminance and it can simulate the natural surface radiation process in a more realistic manner than the Lambertian model. Thus, the Oren-Nayar reflectance model is adopted to correct the incidence angle effect in this study. The distance effect is irregular. Seeking a proper and accurate distance-intensity polynomial may be highly difficult for some scanners. Actually, estimating the specific distance-intensity
function is avoidable. The distance effect is the same for different targets regardless of their surface characteristics and other non-instrumental effects. More specifically, the distance effect can be neutralized when the scanned and reference targets are measured at the same distance even though the specific relationship between distance and intensity is unknown [1].

In the present study, we improve the polynomial method and propose a theoretically rigorous method to derive the hemispherical reflectance from the TLS intensity data. The incidence angle and distance effects are eliminated by the Oren-Nayar reflectance model and reference targets, respectively. The rest of the study is organized as follows. The proposed method is introduced in Section 2. Section 3 outlines the data set. Section 4 presents and discusses the results, followed by some conclusions in Section 5.

2. Method of reflectance modeling

2.1 Physical background of TLS intensity

The TLS sensor transmits a narrow and conical beam of light towards the target, illuminates the surface objects, and records the returned laser pulse signals backscattered from the scanned objects. The total scanning process follows the radar range equation. Since the TLS laser wavelength is most often much smaller than the size of natural targets, extended targets can be considered. For extended targets, the radar range equation can be simplified as [3, 24]:

\[ P_r = \frac{P_t D_r^2}{4\pi R^2 \beta_t^2} \sigma \eta_{sys} \eta_{atm} \]  

(1)

where \( P_r \) is the received laser power, \( P_t \) is the transmitted power, \( D_r \) is the receiver aperture diameter, \( R \) is the distance, \( \beta_t \) is the transmitter beamwidth (\( \beta_t \) is very small), \( \eta_{sys} \) is the system transmission factor, \( \eta_{atm} \) is the atmospheric transmission factor, and \( \sigma \) is the backscatter cross-section. \( \sigma \) can be expressed as:

\[ \sigma = \frac{4\pi}{\Omega} \rho A_t \]  

(2)

where \( \Omega \) is the solid angle, \( \rho \) is the target reflectance at the laser wavelength, and \( A_t = \frac{\pi R^2 \sin \beta_t^2}{4} = \frac{\pi R^2 \beta_t^2}{4} \) is the target effective receiving area.

Both the direction and the strength of the backscatter cross-section are influenced by the type of target reflection (e.g., specular or diffuse) [3]. If the target is a Lambertian, diffuse reflection happens [25]. The radiation is uniformly scattered to a hemisphere rather than at just one direction as in the case of specular reflection (Fig. 1), i.e., \( \Omega = \pi \). According to the Lambert’s cosine law, the backscatter cross-section has a proportionality of the cosine of the incidence angle \( \theta \). Equation (1) can be simplified as [3]:

\[ P_r = \frac{P_t D_r^2 \rho \cos \theta}{4R^2} \eta_{sys} \eta_{atm} \]  

(3)

According to Eq. (3), the target reflectance can be derived as:

\[ \rho = \frac{4P_r R^2}{P_t D_r^2 \cos \theta \eta_{sys} \eta_{atm}} \]  

(4)

However, discrete laser scanner systems do not record the received power \( P_r \). As a result, modeling the reflectance from Eq. (4) is infeasible though \( P_t, D_r, \eta_{sys}, \) and \( \eta_{atm} \) can be considered constants. By merging all the constants, Eq. (3) can be further simplified as:
\[ P_r = C \cdot \rho \cdot \cos \theta \cdot R^{-2} \]  \hspace{1cm} (5)

where \( C = P_s D^2 \eta_{sys} \eta_{adm} / 4 \) is an unknown but constant system parameter.

The recorded intensity \( I \) is often assumed to be the signal amplitude (peak power) of the received echo, i.e., the intensity value is proportional to the number of photons impinging on the detector in a specific time interval [26]. Thus,

\[ I \propto P_r \propto \rho \cdot \cos \theta \cdot R^{-2} \]  \hspace{1cm} (6)

According to Eq. (6), the intensity is directly proportional to the cosine of the incidence angle and inversely proportional to the square of the distance. However, the incidence angle effect is an object property that is mainly related to target scattering properties and surface structure [13, 15]. The \( \cos \theta \) relation is insufficient to correct the incidence angle effect for natural targets whose surface characteristics deviate significantly from that of a Lambertian. Additionally, as a side product to topographic information, TLS intensity measurement is generally intended to enhance the range determination. The raw values of the intensity signal can be modified to obtain an optimal range value [13]. Consequently, the distance effect in TLS, particularly at a short or long distance, is inconsistent with the radar range equation and significantly varies across different laser scanning systems, thereby making it infeasible to model target reflectance directly from Eq. (6).

Considering that the incidence angle and distance effects are theoretically independent of each other and can be solved separately [1, 12], the theoretical incidence angle effect (\( \cos \theta \)) and distance effect (\( R^{-2} \)) in Eq. (6) are replaced with \( f_z(\cos \theta) \) and \( f_3(R) \), respectively, as shown in Eq. (7).

\[ I = f_1(\rho) \cdot f_z(\cos \theta) \cdot f_3(R) \]  \hspace{1cm} (7)

By setting a standard distance \( R_s \) and a standard incidence angle \( \theta_s \), the corrected intensity \( I_c \) that merely depends on the reflectance can be expressed as:

\[ I_c = f_1(\rho) \cdot f_z(\cos \theta_s) \cdot f_3(R_s) = I \cdot \frac{f_z(\cos \theta_s)}{f_z(\cos \theta)} \cdot \frac{f_3(R_s)}{f_3(R)} = I_a \cdot \frac{f_z(R_s)}{f_z(R)} = I_d \cdot \frac{f_z(\cos \theta_s)}{f_z(\cos \theta)} \]  \hspace{1cm} (8)

where \( I_a \) and \( I_d \) are the incidence angle and distance corrected intensity values, respectively. \( I_a \) and \( I_d \) can be expressed as:
In this manner, the points that belong to objects with the same reflectance at the laser signal wavelength and are acquired in the same scan at different incidence angles and distances have similar corrected intensities even if the original intensities vary significantly [12].

TLS intensity is a very complicated function of incidence angle and distance. The incidence angle and distance effects are predominately dependent on the surface characteristics and instrumental effects, respectively. This condition implies that \( f_1(\cos \theta) \) and \( f_3(R) \) vary in different targets and scanners, respectively. \( f_2(\cos \theta) \) should be estimated according to individual surface roughness whereas \( f_3(R) \) should be determined according to specific instrumental effects. In the present study, we propose to estimate \( f_2(\cos \theta) \) by the Oren-Nayar reflectance model that takes into account of the surface roughness. On the contrary, the specific form of \( f_3(R) \) is not estimated because the instrumental effects can be eliminated by reference targets.

2.2 Incidence angle effect correction

The Oren-Nayar model, developed by Michael Oren and Shree K. Nayar, is a physical reflectivity model for diffuse reflection from rough surfaces [27]. Rough surfaces can be modeled as a series of micro-facets with different slopes, where each facet is a small planar diffuse reflector. However, the behaviors of the overall surface constituted by a distribution of perfect diffuse micro-facets deviate significantly from that of a Lambertian reflector [7]. The Oren-Nayar model is a bidirectional reflectance distribution function (BRDF) [28, 29]. It models the reflectance with regards to the directions of incidence and reflection. Compared with the Lambertian model, the Oren-Nayar model which takes individual roughness and micro structure into consideration is more realistic. Therefore, the Oren-Nayar model is more consistent with the real laser reflection conditions of natural surfaces and can accurately and quantitatively simulate the luminance from natural surfaces. The Oren-Nayar model was used to correct the incidence angle effect to obtain a relative intensity value for lithological differentiation in [7].

In TLS, the positions of the emitter and receiver coincide and thus the Oren-Nayar reflectance model can be written as [7]:

\[
L_{out} = L_{in} \cos \theta (A + B \sin \theta \tan \theta)
\]

where \( L_{in} \) and \( L_{out} \) are the received and reflected luminance (intensity), respectively, and

\[
\begin{align*}
A &= 1 - 0.5 \frac{\sigma_{slope}^2}{\sigma_{slope}^2 + 0.33} \\
B &= 0.45 \frac{\sigma_{slope}^2}{\sigma_{slope}^2 + 0.09}
\end{align*}
\]

In Eq. (11), \( \sigma_{slope} \ (\sigma_{slope} \in [0, \pi/2]) \) is the standard deviation of the slope angle distribution of micro-facets in radians. For flat surfaces without facet variation, \( \sigma_{slope} \) is 0°. At this time, the Oren-Nayar model is equal to the Lambertian model [7]. If \( L_{in} \) is 1, the curves of the Oren-Nayar reflectance model with different values of \( \sigma_{slope} \) are shown in Fig. 2. It can...
be seen that the reflected intensity is significantly influenced by $\sigma_{\text{slope}}$ and the Oren-Nayar reflectance model differs considerably with the Lambertian model ($\sigma_{\text{slope}} = 0^\circ$). At small incidence angles, larger values of $\sigma_{\text{slope}}$ lead to less reflected intensity. On the contrary, smaller values of $\sigma_{\text{slope}}$ result in more reflected intensity at large incidence angles. Based on the Oren-Nayar reflectance model, the function of the incidence angle versus intensity in Eq. (7) can be written as:

$$f_z(\cos \theta) = \cos \theta (A + B \sin \theta \tan \theta)$$

(12)

2.3 Distance effect correction

The distance effect mainly depends on the instrumental effects, i.e., the values of $f_z(R)$ are the same for different targets if they are scanned at the same distance. This condition means that the distance effect can be neutralized when the scanned and reference targets are measured at the same distance even though the specific form $f_z(R)$ is unknown, i.e., the estimation of $f_z(R)$ is avoidable [1]. In a small section, $f_z(R)$ can be approximately considered a linear function. Thus, linear interpolation can be utilized to obtain the intensity values within this small section. If a reference target with reflectance $\rho$ is scanned at multiple distances and at an identical incidence angle $\theta$, i.e., the distances satisfy

$$M = R_0 < R_1 < \ldots < R_n = N$$

(13)

a series of discrete points that depict the relationship between distance and intensity can be acquired and stored in a look-up table. We set $I(\rho, \cos \theta, R)$ representing the intensity of a target with reflectance $\rho$ scanned at distance $R$ and incidence angle $\theta$. If a distance $R_i$ satisfies

$$R_i < R_j < \ldots < R_{i+t}, i = 0, 1, \ldots, n-1$$

(14)
The intensity value $I(\rho, \cos \theta, R_y)$ of the reference target at $R_y$ and $\theta_s$ can be calculated based on a linear interpolation between $I(\rho, \cos \theta, R_y)$ and $I(\rho, \cos \theta, R_{s1})$ as shown below:

$$I(\rho, \cos \theta_s, R_y) = \frac{I(\rho, \cos \theta_s, R_{s1}) - I(\rho, \cos \theta_s, R_y)}{R_{s1} - R_y} (R_y - R_s) + I(\rho, \cos \theta, R_y)$$ (15)

Similarly, $I(\rho, \cos \theta_s, R_y)$ at distance $R_y$ can be interpolated. Furthermore, according to Eq. (7), we obtain

$$\begin{cases} I(\rho, \cos \theta_s, R_y) = f_1(\rho) \cdot f_2(\cos \theta_s) \cdot f_3(R_y) \\ I(\rho, \cos \theta_s, R_y) = f_1(\rho) \cdot f_2(\cos \theta_s) \cdot f_3(R_y) \end{cases}$$ (16)

By dividing the two equations in Eq. (16), we have

$$\frac{f_3(R_y)}{f_3(R_s)} = \frac{I(\rho, \cos \theta_s, R_y)}{I(\rho, \cos \theta_s, R_s)}$$ (17)

2.4 Reflectance modeling

The incidence angle and distance effects can be corrected independently. For a specific point with reflectance $\rho_s$ scanned at the incidence angle $\theta_s$ and the distance $R_y$, there are two approaches to model the reflectance:

(I) By combining Eq. (8), Eq. (12), and Eq. (17), the corrected intensity of the scanned point can be expressed as:

$$I_c = I \cdot \frac{f_2(\cos \theta_s)}{f_2(\cos \theta_s)} = \frac{\cos \theta \cdot (A + B \sin \theta \cdot \tan \theta)}{\cos \theta \cdot (A + B \sin \theta \cdot \tan \theta)} \cdot \frac{I(\rho, \cos \theta_s, R_y)}{I(\rho, \cos \theta_s, R_y)}$$ (18)

The corrected intensity $I_c$ only depends on the target reflectance. Generally, the corrected intensity is proportional to the reflectance, i.e., $f_1(\rho)$ is a linear function.

To derive the hemispherical reflectance, the specific form of $f_1(\rho)$ can be estimated by a number of reference targets with known reflectance.

(II) If the standard incidence angle is set to be equal to the incidence angle at which the reference targets are scanned, i.e., $\theta_s = \theta_s$, the incidence angle corrected intensity of the scanned point can be expressed as:

$$I_s = I \cdot \frac{f_2(\cos \theta_s)}{f_2(\cos \theta_s)} = I(\rho, \cos \theta_s, R_y) = f_1(\rho) \cdot f_2(\cos \theta_s) \cdot f_3(R_y)$$ (19)

By dividing Eq. (19) and the first equation of Eq. (16), the reflectance $\rho_s$ of the scanned target can be computed as follows.

$$f_1(\rho_s) = f_1(\rho) \cdot \frac{I(\rho, \cos \theta_s, R_y)}{I(\rho, \cos \theta_s, R_s)} = \frac{I(\rho, \cos \theta_s, R_y)}{I(\rho, \cos \theta_s, R_s) \cdot \cos \theta \cdot (A + B \sin \theta \cdot \tan \theta)}$$ (20)

where $I(\rho, \cos \theta_s, R_y)$ is the intensity value of the reference target interpolated by Eq. (15).
It has to be noted that these two approaches are theoretically the same even though their apparent forms differ significantly. In the first approach, the original intensity is corrected to an arbitrary standard incidence angle which is not necessarily the same as that of the reference targets. When the standard incidence angle is set to be equal to that of the reference targets, the two approaches are exactly equivalent. The second approach is a specific form of the first approach. In practical applications, either of the two approaches can be used to model target reflectance and the incidence angles and distances can be calculated by using the 3D geometrical coordinates of the point cloud. As shown in Fig. 3, the distance is calculated with the original 3D geometric coordinates of the scanned point and the scanner centre. The surface normal is estimated by the best-fitting plane to a neighborhood of points surrounding the point of interest, and then the cosine of the incidence angle can be calculated by the incident radiation vector and the surface normal vector.

![Fig. 3. Calculation of incidence angle and distance.](image)

### 2.5 Estimation of $\sigma_{\text{slope}}$

A vital parameter of the proposed method is the standard deviation of the slope angle distribution of micro-facets $\sigma_{\text{slope}}$. The parameter $\sigma_{\text{slope}}$ depends only on the surface roughness. It differs significantly for different targets with different surface structures and should be individually estimated [12]. Even a small difference in $\sigma_{\text{slope}}$ would have a significant impact on the retrieved reflectance. We propose a new method to determine the optimal value of $\sigma_{\text{slope}}$ for a certain surface with reflectance $\rho$ in this study. Firstly, a data set $I(\rho,\cos \theta, R) \ (i = 1, 2, \ldots, m)$ where $m$ is the number of point cloud) of this surface with different incidence angles and distances is sampled. Then, all the points are corrected for the distance effect to obtain the distance independent intensities $I_d(\rho, \cos \theta, R)$ according to Eq. (17) with an arbitrary standard distance $R$. Finally, by choosing any one of the incidence angles as the standard incidence angle, e.g., $\theta_i = \theta_j, j \in i$, all the distance corrected intensities are further corrected for the incidence angle effect according to Eq. (12) with a value of $\sigma_{\text{slope}}$ from $0^\circ$ to $90^\circ$ in steps of $1^\circ$. Theoretically, the final corrected intensities $I_d(\rho, \cos \theta, R)$ should be equal to the distance corrected intensity $I_d(\rho, \cos \theta, R_j)$ at the incidence angle $\theta_j$. Therefore, we can find the optimal value of $\sigma_{\text{slope}}$ for the surface by comparing the corrected intensities $I_d(\rho, \cos \theta, R)$ with $I_d(\rho, \cos \theta, R_j)$ as follows.

$$f(\sigma_{\text{slope}}) = \sum_{j=1}^{m} \left[ I_{\infty}^{\sigma/2}(\rho, \cos \theta, R) - I_d(\rho, \cos \theta, R_j) \right]$$

where $I_{\infty}^{\sigma/2}(\rho, \cos \theta, R)$ represent the incidence angle corrected intensities with a value of $\sigma_{\text{slope}}$ from $0^\circ$ to $90^\circ$ in steps of $1^\circ$. The optimal value of $\sigma_{\text{slope}}$ for the surface is the one at
which \( f(\sigma_{\text{slope}}) \) reaches the minimum value. It is worth noticing that the optimal value of \( \sigma_{\text{slope}} \) for a surface does not depend on instrumental properties, i.e., \( \sigma_{\text{slope}} \) for a surface estimated by the data of one scanner can be directly used to correct the data of this surface scanned by another scanner.

3. Distance experiments and data sets

3.1 Distance experiments of reference targets

To provide a reference for the interpolation of the distance effect, four reference targets with a size of 10 cm \( \times \) 10 cm and reflectance of 20\%, 40\%, 60\%, and 80\% were mounted on a board and scanned at a series of distances. The scanner used was Faro Focus\textsuperscript{3D} 120, which is a continuous wave 905 nm terrestrial laser scanner that delivers 3D geometric information and returning intensity values recorded in 11 bits \([0, 2048]\). The board directly faced the scanner to minimize the incidence angle effect and was placed at distances from 1 m to 5 m (in steps of 1 m) and 5 m to 29 m (in steps of 2 m). A total of 17 scans were obtained and the incidence angles of all the four targets at each scan were 0\°. The original instrumental intensity data were extracted in a point cloud image created by the standard software Faro SCENE. For each reference target in this experiment, the average intensity value over a sampled surface was used for analysis. The surface data of the targets were manually sampled as fully as possible. The results of the distance experiments are shown in Fig. 4. Generally, the distance effect of Faro Focus\textsuperscript{3D} 120 strongly deviates from the radar range equation and there approximately exists a linear relationship between each neighbor distance section. Specifically, the original intensity decreases for short distances below 3 m, drastically from 1 m to 2 m and then marginally from 2 m to 3 m. Thereafter, the intensity increases significantly from 3 m to 5 m, followed by a steep decrease from 5 m to 15 m. Finally, the intensity begins to level out for ranges over 15 m.

![Fig. 4. Original intensity with respect to distance for the four reference targets (\( \theta = 0^\circ \)).](image)

3.2 Natural surfaces

To validate the proposed method, we used the Faro Focus\textsuperscript{3D} 120 scanner to scan a white lime wall, a cement road, a building facade with gray bricks, a concrete metro tunnel, a dry soil pit of an archaeological site, and some branches of camphor trees. These data were obtained from different scanning campaigns with totally different instrumental settings (e.g., scanning mode, quality, and resolution) and external environment. The original intensity images of the six surfaces are shown in Fig. 5. The surface roughness of these six targets differs significantly.
A total of 20 small regions, with a size of approximately 15cm × 15cm, in the six surfaces with different incidence angles and distances were manually and randomly sampled. The mean original intensity values of the selected regions are displayed in Fig. 6 and the distances and cosine of the incidence angles are displayed in Fig. 7. Visually, excessive overlaps exist in the original intensity data of these surfaces; distinguishing these surfaces based on the original intensity data is impossible.

Fig. 5. Original intensity image. (a) White lime wall. (b) Building facade with gray bricks. (c) Cement road. (d) Metro tunnel. (e) Dry soil pit. (f) Camphor tree branches.

Fig. 6. Original intensity values of the sampled regions of the six surfaces. The horizontal axis is the region identification (ID) of these sampled regions.
4. Results and discussion

To correct the intensity data, $\sigma_{\text{slope}}$ should be firstly determined. A data set from each of the six surfaces was sampled and then the optimal value of $\sigma_{\text{slope}}$ for each surface was separately estimated by the sampled data set according to Eq. (21). The optimal values for the six surfaces are shown in Table 1. Due to the variations in surface roughness, the optimal values of $\sigma_{\text{slope}}$ differ significantly from 37° to 62° for the six surfaces.

Table 1. Optimal Values of $\sigma_{\text{slope}}$ for the Six Surfaces

|          | Wall | Building | Road | Tunnel | Soil | Branch |
|----------|------|----------|------|--------|------|--------|
| Value    | 40°  | 49°      | 62°  | 58°    | 52°  | 37°    |

The second approach was used to model the reflectance in this study. Firstly, the incidence angle corrected intensity values ($\theta = 0^\circ$) of the 120 sampled regions were calculated according to Eq. (19). The incidence angle corrected intensity values of the 120 sampled regions with different values of $\sigma_{\text{slope}}$ from 0° to 90° in steps of 1° are shown in Fig. 8 where the green and red curves represent the incidence angle corrected intensity values by the optimal value of $\sigma_{\text{slope}}$ and the Lambert’s cosine law ($\sigma_{\text{slope}} = 0^\circ$), respectively. Obviously, $\sigma_{\text{slope}}$ is vital for the correction of the incidence angle effect; different values of $\sigma_{\text{slope}}$ lead to totally different correction results of the same surface. In particular, the results of the Lambert’s cosine law deviate significantly from those of the optimal values of $\sigma_{\text{slope}}$, which demonstrates that the Lambert’s cosine law is not suitable for the correction of the incidence angle effect of natural surfaces. Moreover, the optimal value of $\sigma_{\text{slope}}$ of a surface cannot be applied to another surface with different surface roughness. For example, the optimal values of $\sigma_{\text{slope}}$ of the other four surfaces were used to correct the incidence angle effect of the cement road and the metro tunnel. The results are shown in Fig. 9. It can be seen that even a small difference in $\sigma_{\text{slope}}$ can lead to significant variations in the correction results. Consequently, $\sigma_{\text{slope}}$ should be estimated individually for different targets.
Fig. 8. Incidence angle corrected intensity values of the sampled regions with different values of $\sigma_{\text{slope}}$ from 0° to 90° in steps of 1°. (a) White lime wall. (b) Building facade with gray bricks. (c) Cement road. (d) Metro tunnel. (e) Dry soil pit. (f) Camphor tree branches.
Fig. 9. Optimal values of $\sigma_{\text{slope}}$ of the other four surfaces were used to correct the incidence angle effect of the cement road and the metro tunnel. (a) Cement road ($62^\circ$). (b) Metro tunnel ($58^\circ$).

The interpolated intensity values of the four reference targets at the same distances as the sampled regions of the six surfaces according to Eq. (15) and Fig. 4 are shown in Fig. 10. Also, the incidence angle corrected intensity values of the six surfaces by the optimal values of $\sigma_{\text{slope}}$ in Table 1 are shown in Fig. 10. It can be seen that the incidence angle corrected intensities of the sampled regions of the six surfaces are proportional to the distance interpolated intensity values of the four reference targets, i.e., the curves in Figs. 10(a)–10(f) exhibit the similar trends. This result reveals that the intensity is proportional to the reflectance if two targets are scanned at the same incidence angle and distance. That is to say, we can roughly predict the reflectance values of the six surfaces from Fig. 10. For example, the reflectance of the building should be between 40% and 60% as the curve of the incidence angle corrected intensities of the building is between that of the 60% and 40% targets (Fig. 10(b)).
Fig. 10. Interpolated intensities of the four reference targets at the same distances as the sampled regions and incidence angle corrected intensities ($\theta_i = 0^\circ$) of the six surfaces. (a) Wall. (b) Building. (c) Road. (d) Tunnel. (e) Soil. (f) Branch.

For Faro Focus3D 120, the intensity is scaled with a constant and an offset, which results in an offset $\rho_{\text{off}}$ in the reflectance [20]. This result can be verified in Fig. 4, where a linear relationship exists between the intensity and the reflectance given that the distance and the incidence angle are the same. Thus, Eq. (20) is rewritten as follows:
The value of $\rho_{\text{off}}$ can be estimated by the data of the four reference targets scanned at the same distance and incidence angle in Fig. 4. By using the 80% target as a reference, the corrected intensity values of the 20%, 40%, and 60% targets can be calculated. For example, $I_c(20\%, \cos\theta, R) = I_c(80\%, \cos\theta, R) \cdot \frac{I(20\%, \cos\theta, R)}{I(80\%, \cos\theta, R)}$. By setting $I_c(80\%, \cos\theta, R)=1$ (the corrected intensity value of the 80% target can be arbitrarily set), the corrected intensity values of the 20% target $I_c(20\%, \cos\theta, R)$ can be calculated. Similarly, the corrected intensity values of the 40% and 60% targets can be obtained. The relationship between the corrected intensity and the reflectance of the three targets is shown in Fig. 11. Linear regression between the corrected intensity and true reflectance was conducted and $\rho_{\text{off}}$ was the ratio of the line intercept and slope. $\rho_{\text{off}}$ was calculated as 2.0554 (0.7198/0.3502) for Faro Focus$^{3D}$ 120 by the data in Fig. 11. With the data of the six natural surfaces and the four reference targets in Fig. 10, the reflectance values of the sampled regions of the six surfaces can be obtained according to Eq. (22). The retrieved reflectance values are shown in Fig. 12 and Table 2.

\[
\rho_{\text{off}} = \left(\rho_{\text{on}} + \rho_{\text{off}}\right) \cdot \frac{I\left(\rho_{\text{on}}, \cos\theta, R\right)}{I\left(\rho_{\text{off}}, \cos\theta, R\right)} - \rho_{\text{off}}
\]

Fig. 11. Relationship between the corrected intensities and the reflectance values of the 20%, 40%, and 60% targets. The 80% target is used as a reference and the corrected intensity value of the 80% target was set as 1.

As shown in Fig. 6, the original intensity is influenced by the incidence angle and distance. As such, the intensity values of different regions of the same target differ significantly although they have the same scattering property. Nevertheless, the retrieved reflectance values of different regions of the same target are approximated and the reflectance values by using different reference targets are similar, as shown in Fig. 12 and Table 2. However, there exist some variations in the retrieved reflectance values of different regions because these sampled regions may not be exactly homogeneous. The mean reflectance values by using the four reference targets are shown in Fig. 13, which are considered the final retrieved reflectance. Generally, distinguishing these surfaces based on the retrieved reflectance values becomes feasible. Since the true reflectance values of the building, tunnel, soil, and branch are close, several overlaps exist in the retrieved reflectance values of these four surfaces.
To evaluate the results quantitatively, we used the FieldSpec Pro spectrometer manufactured by the Analytical Spectral Devices Inc. to measure the reflectance values of the six surfaces. The reflectance values of the six surfaces measured by the spectrometer at the wavelength of 905 nm are 78%, 49%, 27%, 43%, 56%, and 42%, which are considered the true reflectance values (each surface was measured ten times to obtain the mean reflectance). As shown in Table 2, the deviation of the retrieved reflectance values of the six natural surfaces from the reflectance values measured by the spectrometer is approximately 4.29% and the RMSE is 0.0562. This quantitative result proves the high accuracy of the proposed method in modeling reflectance.

Fig. 12. Retrieved reflectance values of the sampled regions of the six surfaces. (a) The 80% target is used as a reference. (b) The 60% target is used as a reference. (c) The 40% target is used as a reference. (d) The 20% target is used as a reference.
Table 2. Retrieved Reflectance Values of the Six Surfaces by Using Different Reference Targets

| Reference target | 80%   | 60%   | 40%   | 20%   | Mean Standard |
|------------------|-------|-------|-------|-------|---------------|
| Wall             | 78.10%| 76.54%| 74.88%| 72.40%| 75.48%        |
| Building         | 51.01%| 50.45%| 50.38%| 49.24%| 50.27%        |
| Road             | 30.69%| 29.46%| 28.87%| 26.29%| 28.83%        |
| Tunnel           | 41.72%| 40.87%| 40.56%| 39.51%| 40.67%        |
| Soil             | 57.49%| 57.37%| 57.73%| 58.14%| 57.68%        |
| Branch           | 42.29%| 41.37%| 40.91%| 39.24%| 40.95%        |

5. Conclusion

This study proposed a new method to retrieve the hemispherical reflectance values from the intensity data of TLS. This is a promising method especially in the context of current developments of multi-spectral LiDAR systems [8, 30]. Significant advantages of the proposed method are that the surface roughness is specially considered in the correction of the incidence angle effect and estimating the specific function form of distance versus intensity is no longer necessary when the scanned and reference targets are measured at the same distance. Theoretically, the method can be extended to other instruments and targets. However, the applicability to other scanners and other natural surfaces should be further tested.

Future work should consider the stability of the systematic parameters, such as the emitted power, to improve and optimize the model. The retrieved reflectance depends only on the target characteristics and the wavelength. Therefore, the data from two campaigns by the same scanner under different instrumental parameters or by different scanners using the same wavelength are directly comparable. In multi-sensor cases, the laser wavelengths should also be considered. Nevertheless, the retrieved reflectance still can provide a comparable criterion at some extent as most laser scanner systems operate in the near-infrared region of the electromagnetic spectrum.

Funding

National Natural Science Foundation of China (NSFC) (41671449); National Science and Technology Support Program of China (2013BAK08B07); NASG Key Laboratory of Land Environment and Disaster Monitoring (LEDM2014B05).