Intensity Correction of Terrestrial Laser Scanning Data by Estimating Laser Transmission Function

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Abstract—Intensity information, recorded by laser scanning, shows great potential for research and applications (e.g., object recognition and registration of images to 3-D models). Multiple studies not only show the significance and possibility of correcting the intensity value but also highlight the existing problems, i.e., that the near-distance and angle-of-incidence effects prevent the practical correction of a terrestrial laser scanner (TLS). In this paper, we explore the near-distance corrections for Z+F Imager5006i, a commercially available coaxial TLS, and propose a corresponding method to correct the range or distance effects on its output intensity data. This method estimates the parameters of customized range-intensity equations using a novel sample data collection design. Using the angle-of-incidence correction method, practical intensity corrections were conducted on TLS point cloud data from white walls and Mogao Grottoes, Dunhuang, China. The results were visualized and show the effectiveness of the proposed method. In addition, we analyzed the new problems that emerge after correction and outline further studies.

Index Terms—Correction, intensity, laser transmission function, terrestrial laser scanning (TLS).

I. INTRODUCTION

T ERRESTRIAL laser scanning (TLS) is one of the most significant spatial data acquisition developments in surveying and mapping areas during the past two decades. TLS provides direct and high-speed 3-D point cloud data capture by measuring the distance from the sensor to a point on the object surface and the laser beam direction. Because of its practical applications, TLS is employed in many areas, including digital factory, virtual reality, architecture, civil engineering, archeology and cultural heritage, plant design, space applications, and automation systems (robotics).

The range is determined by computing the time of flight between emitting and receiving the laser signal. There are three ways to obtain the range value: 1) pulsed ranging; 2) amplitude-modulated continuous-wave (AMCW) ranging; and 3) frequency-modulated continuous-wave ranging [1], [2]. The azimuth and inclination directions of laser beams are determined by means of an angle measurement system commonly used on total stations and theodolites. Thus, for each point, 3-D coordinates \((x, y, z)\) can be calculated from range, inclination angle, and azimuth angle. In addition, the system can receive the power from the backscattered laser signal of each point and record it as an intensity value.

Currently, most TLS applications and projects only make use of the geometric information instead of intensity information that represents the radiation properties of object surfaces. Applications that do employ TLS intensity information are often found in the fields of forestry, glaciology, and geology [3]–[5]. Due to recent technological developments, the density of point cloud has rapidly increased, and intensity data usage in new applications in other fields, such as object recognition and registration of 2-D images to 3-D models, has become possible [6]–[9]. Since intensity values are significantly affected by factors related to the surface characteristics of objects and laser transmission from the emitter to the surface of the object and back to the receiver, correction of TLS intensity data will benefit those applications.

In order to investigate and elucidate the physical principles of some factors that influence intensity values and to develop a solution to correct them, we implemented our method on data collected with a coaxial TLS Z+F Imager5006i (the specifications are detailed in Section III-A). The objectives and contributions of this paper are as follows:

1) give a short review of recent work considering TLS intensity correction (see Section II);
2) explore the near-distance effect [10], [11] by summarizing the physical principles of TLS systems on intensity generation (see Section III-B);
3) introduce a model-driven intensity correction method with parameter estimation (see Section III-C and D).

Unlike other papers that treat the correction of TLS intensity data as a research method confined within the existing theoretical models of TLS, we searched for correction methods across the entire range of procedures for laser transmission, particularly focusing on the inner mechanisms of TLS. We identified the mechanism of TLS on intensity acquisition and estimated the related parameters for subsequent correction. To demonstrate the practical effectiveness of this method, correction results of TLS data from two different scenes are presented in Section IV. Section V analyzes these results, and Section VI concludes with the findings.

II. LITERATURE REVIEW

Previous research has investigated the intensity generation principles of airborne laser scanning (ALS) in terms of the...
intensity correction of laser scanning systems [12]–[15]. Because the fundamental principles are similar, some of the factors that affect the intensity data of airborne systems also affect terrestrial systems. Several methods have been proposed, including data- and model-driven methods [13], [16] to correct the intensity data of TLS. According to [12], factors that affect the intensity data of ALS are basic physics (such as initial pulse energy, atmospheric loss, range, and angle of incidence), surface properties (such as moisture of the object), and instrumental signal processing [such as automatic gain control (AGC)]. However, for close-range TLS, atmospheric transmission effects can be neglected. If TLS employs AMCW to measure the distance, pulsed energy correction is also unnecessary [17]. Of the remaining factors, range and angle of incidence have the largest influence on intensity data and are thus the focus of almost all research on correcting TLS intensity.

Theoretically, based on the equation of light transmission, the backscattered intensity of TLS is inversely proportional to the range squared; hence, the relationship can be described as \(I \propto 1/R^2\), where \(I\) is a constant, and \(R\) represents the range. However, empirical data are inconsistent with \(I \propto 1/R^2\). Many mechanisms have been proposed to explain this inconsistency [10], [11], [13]–[15]. The logarithmic effect, also called AGC, can amplify weak backscatter laser signals [10], [13], thus explaining the inconsistency found in the empirical data at large ranges. However, for the near ranges, discrepancy becomes even more significant and is termed the near-distance effect, prompting more mechanisms for correction. At first, the near-distance effect was attributed to an incomplete overlap between a laser beam and the receiver’s field of view [18]. This explanation is true for biaxial laser scanning systems but is incorrect for coaxial systems. A previous study [10] considered near-distance discrepancy from \(K/R^2\) dependence as an artifact caused by the automatic brightness reducer (ABR) for near distances. However, the TLS (particularly the AMCW phase-shift type) collects data very fast (up to 1 million points/s) that the ABR’s time response can be exceeded. In addition, to protect the sensor, the ABR should only be intensity-dependent, therefore cannot explain the near-distance inconsistency, which is range-dependent, as inferred from the observation that the shape of the range–intensity curve is similar among objects with different reflectances [11], [19]. The latest proposed explanation for the near-distance effect links it to the receiver optics’ defocusing effect that exists in both biaxial and coaxial systems [20].

As for the incidence angle factor, the bidirectional reflectance distribution function (BRDF) is a general model to describe the interaction between the incidence light beam and the object surface [21]. However, this model requires \textit{a priori} information about the object surface (roughness, permittivity, etc.) to be put into practical application. To avoid this, direct research on the relationship between the intensity of TLS and the incidence angle to the object surface was conducted [22]. Qualitative analysis found that TLS intensity is independent of the incidence angle when the surface of the scanned object is irregular (macro-roughness) [23]. Therefore, incidence angle correction of the TLS intensity data will consider the effect of surface roughness to show its effectiveness [11]. Surface macro-roughness may also depend on environmental factors such as surface moisture content [24] (i.e., relative humidity and temperature).

The radiation model of the laser intensity value is very complex that the intensity data cannot be corrected by using simple digital image processing methods such as low-pass filtering and contrast enhancement. Although data-driven methods derive estimation functions from theoretical models, their estimated parameters are data dependent and unstable without initial values. To correct for the near-distance effect on intensity, the defocusing effect of the receiver’s optics was used to formulate the laser transmission model for the TLS laser scanner. This customized computational model is analyzed to provide the estimation function and initial values. Next, the parameters of the transmission function were estimated using sample data collected using a novel design. These parameters were then employed to correct two different kinds of data to demonstrate the effectiveness of this method. Finally, the effect of the correction method was evaluated. The analysis of the defocusing effect of the receiver’s optics provides a good explanation of the near-distance effect. Thus, range effects on our TLS intensity were nearly completely eliminated.

### III. Correction Methods

#### A. Intensity Data of TLS

The intensity values of TLS are recorded as digital numbers and represent laser returns proportional to the number of photons impinging on the detector [25]. Specifically, the intensity value of an AMCW TLS is defined by Hug and Wehr as the amplitude of the returned signal, proportional to the average received signal and carrier power when the signal is the sinusoidal echo profile [26]. Experimental data were collected using a coaxial AMCW TLS, i.e., Z+F Imager5006i [27]. Its recorded laser intensity was defined as the returned laser power, which can be easily measured using standard circuits.

Z+F Imager5006i transmits 632.8-nm laser light and employs AMCW technique to measure the distance with an ambiguity range of 79 m. The range noise is 0.4–7 mm. The scanner’s azimuth and inclination field of view are 360° and 155°, respectively; thus, the collected range and intensity data can be displayed as a panorama image with a 360° width and a 155° height (see the next section for details). In the original TLS data, a point’s position is recorded in a spherical coordinate system specified by three numbers, namely, range, inclination/zenith angle, and azimuth angle. The original point is set to the rotation pivot of the scanner. The backscattered laser intensity is then scaled to an integer increment based on zero. Then, the postprocessing software imports the original records and exports measured point data as \(X, Y, Z, \text{ and } I\). The angular resolutions in both inclination and azimuth directions of the TLS angle measure system are very high (sampling interval is 0.0018° for Z+F Imager5006i) that the exported points are dense enough to be called as point cloud. To improve the visual appearance, software such as Leica Cyclone will arbitrarily rescale the intensity data, unavoidably distorting it in the process [5], [7], [11], [28]. Therefore, in the experiments described...
in this paper, the ranges and intensities were read directly from the original recorded files (zfs for Z+F Imager5006i). Before correction, the incidence angles were calculated by a normal fitting with neighboring points. To ensure correct surface normal estimation, the neighborhood was defined as spherical volume with a diameter twice the planar accuracy of the point cloud. For low point density areas, the neighborhood diameter was increased to retain enough points to estimate a plane.

B. Laser Transmission Function of TLS

The physical principles of the TLS for backscattered laser strength from the object surface follow the LiDAR equation, which describes the relationship between the received laser power and the emitted laser power [29]. Therefore, the intensity value obtained by Z+F Imager5006i is proportional to the received laser power defined by the LiDAR equation simplified as (see the Appendix for more details)

$$P_R = \frac{C_E \rho \cos \alpha}{R^2}$$

(1)

where $C_E$ is a constant when the average emitted laser power is fixed. $P_R$ is proportional to the intensity and recorded by TLS at the same time the range $R$ is measured. $\alpha$ is the incidence angle that can be estimated by a normal fitting of collected 3-D near-neighbor points, and $C_E$ can be estimated with the TLS point cloud data from a given surface of a specific kind of material (reflectance of the object $\rho$ is constant). Therefore, range and incidence angle effects on intensity are theoretically independent from each other and can be solved separately.

1) Near-Distance Effect on TLS Intensity: Equation (1) is an ideal model under assumptions of extended Lambertian object surface conditions and ideal emitter–receiver configurations. However, in reality, data collected with TLS usually show different intensity–range relationships than such an ideal physical model (LiDAR equation) at near distances [11, 30]. For these close-range LiDAR returns, two possible factors were considered, namely, defocusing of the receiver’s optics and incomplete overlap between the laser beam and the receiver’s field of view [20]. The incomplete overlap problem exists only in biaxial (parallel axial) systems and therefore was dismissed. The defocusing effect exists both in coaxial and biaxial systems. The function of the receiver’s optics is to focus the returned laser onto the detector using either a lens or a concave mirror. Because of the function of a concave mirror on laser signal is similar to that of a lens, in the following text, only the lens was considered.

The near-distance effect of a coaxial TLS can be described as the ratio of the input laser signal captured by the detector from limited and unlimited ranges, as $R$ and $\infty$ in (2) ($r_d, d, D, S_d,$ and $f$ are parameters of TLS; see the detailed derivation in the Appendix)

$$\eta(R) = \frac{P(R)}{P(\infty)} = 1 - \exp \left\{ -\frac{2r_d^2(R + d)^2}{D^2 \left[ (1 - \frac{S_d}{D}) R + d - \frac{dS_d}{f} + S_d \right]^2} \right\}.$$  

(2)

Thus, combining with (1), the intensity value for coaxial TLS considering the near-distance effect is

$$I(R, \alpha, \rho) \propto P(R, \alpha, \rho) = \eta(R) \frac{C_E \rho \cos \alpha}{R^2}.$$  

(3)

In these formulas, if the detector is placed on the focus point ($S_d = f$), then (2) can be written as

$$\eta(R) = 1 - \exp \left\{ -\frac{2r_d^2(R + d)^2}{D^2S_d^2} \right\}$$  

(4)

which is a typical upside-down normal distribution. At close ranges, $\eta(R)$ is small but increases sharply as $R$ increases; at far distances, $\eta(R)$ remains almost at 1.0 and the shape of $I(R, \alpha, \rho)$ becomes similar to $K/R^2$.

2) Incidence Angle: The incidence angle effect is one of the factors related to viewing geometry such as emergent angle $e$, incidence angle $\alpha$, and the azimuthal angle $t$ between them, as well as to the surface properties (reflectance, roughness, etc.) [21]. The TLS corrected in this instance is a coaxial system; hence, $\alpha = e = t$ is the only angle considered as a variable in the LiDAR equation. The effect of the incidence angle on the intensity is approximately given as follows [11]:

$$I(\alpha) \propto m \left[ 1 - n \left( 1 - \cos \alpha \right) \right] = m(1 - n + n \cos \alpha)$$  

(5)

where $m$ is mainly proportional to the object reflectance, which is denoted by $\rho$, and $n$ is related to the roughness of the object surface. Thus, the factor equation of the incidence angle can be written as

$$I(\alpha) = h(1 - n + n \cos \alpha)$$  

(6)

where $h$ is a constant. Finally, combined with (3), (6) becomes

$$I(R, \alpha, \rho) = \eta(R) \frac{C_E \rho(1 - n + n \cos \alpha)}{R^2}$$  

(7)

where $C_E = hC_E = (hP_E D^2 / 4) \eta_{\text{Sys}} \eta_{\text{Atm}}$. Equation (7) is an improvement of the LiDAR equation with consideration of near-distance effect and incidence angle, thus termed the TLS laser transmission function in this paper.

Observing from (7), the effects of range and incidence angle on intensity are independent, thus can be corrected separately by parameter estimation.

C. Range Effect Correction

Although a physical model of coaxial laser scanning systems is given, the intensity correction cannot be achieved by simply calculating (7). The technical parameters vary with different laser scanning systems and working environments: Intensity correction using a model-driven method should be based on some assumptions [13]. For a given coaxial TLS, the size of the detector and focal length of the receiver’s optic are generally unknown. Therefore, a model-driven method with parameter estimation was chosen, in which (7) is the estimation function and the unknown parameters or their combinations were estimated using controlled verification experiments. For stable estimation, a monotonic relationship must be made between the recorded intensity and the factor (range or incidence angle). Therefore, the estimation function is divided.
Fig. 1. Distribution of the targets and scanners.

Fig. 2. Collected point clouds displayed with intensity, the intensity on near targets apparently lower than the farther away ones.

Fig. 3. Fitting results of (8) for the white targets. The points are collected sample data in which parameters in (8) were optimally fitted to a curve shown as a solid line.

TABLE I

<table>
<thead>
<tr>
<th>Parameters</th>
<th>l(inc)</th>
<th>r(d)</th>
<th>d(m)</th>
<th>D(m)</th>
<th>S(d)</th>
<th>f(m)</th>
</tr>
</thead>
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<tr>
<td>Lower</td>
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<td>0.0</td>
<td>-1.0</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Upper</td>
<td>Inf</td>
<td>0.005</td>
<td>0.2</td>
<td>0.6</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Initials</td>
<td>3e+8</td>
<td>1e-3</td>
<td>-0.18</td>
<td>0.05</td>
<td>0.18</td>
<td>0.15</td>
</tr>
<tr>
<td>Optimized</td>
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<td>2.5e-3</td>
<td>-0.7538</td>
<td>0.05035</td>
<td>0.1608</td>
<td>0.1704</td>
</tr>
</tbody>
</table>

5 m, the intensity shifts away from the \( K/R^2 \) pattern due to the defocusing effect of the receiver’s optics.

2) Parameter Estimation: Because the reflectance of white paper is constant and the incidence angle \( \alpha \) is zero, then \( p = C_E \rho (1 - n + n \cos \alpha) = h C_E \rho \) is a constant. Thus, the intensity–range function can be simplified from (7) as follows:

\[
F(R) = \frac{p}{R^2} \left\{ \exp \left\{ -\frac{-2r_d^2(R + d)^2}{D^2 \left( 1 - \frac{S_d}{f} \right)} \right\} \right. \\
\left. \left( R + d - \frac{d S_d}{f} + S_d \right)^2 \right\} .
\]

Since the parameters \( E = (p, r_d, d, D, S_d, f) \) have a physical basis, their probable initial values and range can be predicted for faster and better estimation results. As shown in Table I, the parameters in (8) can be estimated in accordance with observed values such as the receiver’s diameter \( D \) and the detector’s distance from the lens plane (observed directly from the scanner and from its patent) by iterative curve fitting using a nonlinear least squares method and robust Gauss–Newton algorithm.
3) Range Correction: According to (7), the intensity is proportional to the surface reflectance if the range, the incidence angle, and the surface roughness are constant. Thus, range–intensity curves for surfaces with different reflectances are of the same shape. Fig. 3 shows excellent agreement between experimental data (points) and theoretical prediction using optimized parameters given in Table I. Therefore, by dividing the measured intensities with intensities of white paper at the same range, the relative reflectance of the surface to the white paper can be generated. Moreover, the intensity variances introduced by different ranges can be corrected.

D. Incidence Angle Effect Correction

1) Sample Data Collection: Because the effect of the incidence angle is dependent on both surface properties of the object, as well as measured range, sample data for parameter estimation must be collected from range-invariant or range-corrected point cloud data using a homogeneous surface. As shown in Fig. 4, the targets were placed with different angles to the radius of a circle centered with laser scanner’s rotation pivot.

Fig. 5 is the resulting output image from Z+F Imager5006i, in which the apparent brightness of the target cards monotonically decreases with increasing incidence angle, although the cards have uniform surface.

As shown in Fig. 6(a), sample data were collected at multiple ranges (1–11 m); for every range, the angle of incidence varies from 0° to 80° with about 1° interval. Fig. 6(b) shows normalized intensities at each range as almost merged as one curve, thus experimentally demonstrating the independent relationship between the effects of range and angle of incidence. This independence was also previously confirmed [11], and the cause was found to be instrumental, whereas the angle of incidence was shown to be related to the surface characteristics of objects. Therefore, range-corrected point cloud data can be also used as sample data for angle-of-incidence effect correction.

2) Parameter Estimation: According to (7), the estimation function can be written as

\[ F(\alpha) = h \rho (1 - n + n \cos \alpha) . \]  

To get an accurate surface parameter \( n \) in (9) for intensity correction, sample intensity data were collected from white walls (see the next section for details) after range correction. The corresponding incidence angles were calculated by plane fitting the points on the white wall using a spherical neighborhood with an \( r \) diameter. To ensure correct normal estimation, \( r \) is determined as at least twice the ranging accuracy of the point cloud on the wall surface. As shown in Fig. 7, 160 sample...
The estimation results by optimized curve fitting of (9) are $h_\rho = 2.924$ and $n = 0.9943$.

3) Incidence Angle Correction: According to (9), the effect of the incidence angle on intensity is dependent on the roughness of the scanned surface; hence, the corrected data is assumed to be homogeneous in roughness. Fig. 7 shows great agreement between sample data and theoretical model. Thus, the effect of the incidence angle can be eliminated by multiplying the intensity with the reciprocal of (9) with the corresponding incidence angle at constant range.

IV. VALIDATION EXPERIMENTS

Backscattered laser intensities from homogeneous objects show apparent variations due to the effects of range and incidence angle. Thus, a visual comparison of intensity images before and after corrections is the most straightforward evaluation method. In addition, a mathematical evaluation using box charts and histograms compares intensity from homogeneous object surfaces before and after corrections. Sharp convergence of intensity distributions was expected after corrections.

A. Experiment 1: White Wall Office

A white wall in an empty room serves as a good homogeneous object for observing the effectiveness of the intensity correction. It also serves as an ideal planar surface from which sample data can be collected to estimate the intensity–incidence angle function. The position of the scanner in the office and the 3-D point cloud data are visualized in Fig. 8(a). The original intensity data is displayed as a panorama image in Fig. 8(b), whose variations are noticeable on the white walls in different areas. The range correction results are displayed in Fig. 8(d).
By referring the range image in Fig. 8(c), it is apparent that, after eliminating the near-distance effect, the overall intensity values increase and the effect of the incidence angle on intensity becomes visible. The final correction result was shown in Fig. 8(e).

**B. Experiment 2: Cave of Mogao Grottoes**

Efforts have been undertaken to preserve the Mogao Grottoes, a famous world heritage site located in Dunhuang, Gansu Province, China, in the form of digital mural images and 3-D models. To achieve high fidelity in the mural documentation data, the resolution of the collected digital mural images must be sufficiently high. A variety of images must therefore be stitched together to create one complete mural image. The accumulated errors induced by image merging can be eliminated by referencing the mural images to the laser scanning intensity data with accurate 3-D geometrical information. Therefore, intensity correction of the laser scanning data is of significant importance for the digital preservation of the Mogao Grottoes.

As the roughness of the walls appears to be similar throughout the room, the estimated parameters of (9) for the white wall office were applied to the intensity data from one of the Mogao Grottoes with nonhomogenous surfaces to correct the incidence angle effect. The results are shown in Fig. 9. In analogy to Fig. 8, Fig. 9(a) shows a schematic planar (left) and 3-D (right) visualization of scanner position in the cave. The point cloud data are shown in Fig. 9(b)–(e) as original intensity, range, range-corrected, and final corrected images, respectively. They provide a comparison by inspection of intensity before and after corrections.

**V. EVALUATIONS AND DISCUSSION**

**A. Evaluation**

A statistical analysis of the digitized intensity data was conducted by comparing the box charts (see the top row of Fig. 10) and histograms (see the bottom row of Fig. 10) of the intensity data for the white wall experiment before and after data correction. As shown in Fig. 10(a) and (c), before correction, the intensity data from a homogenous object shows wide variance both among and within specific areas. After correction, the intensity data cluster shows similar means and variances within a small interval, thus demonstrating a significant reduction of intensity variances [see Fig. 10(b) and (d)]. This experiment essentially validates our model assumptions since the walls in this case are known *a priori* to be homogeneous.

**B. Discussion**

The corrections of the range and angle effects, based on the estimation of laser transmission functions, show a significant reduction of the variations in the TLS intensity data. The near-distance effect is apparently eliminated after conducting range correction [see Figs. 8(b)–(d) and 9(b)–(d)]. As shown in rectangles and circles in Figs. 8(d) and 9(d), the incidence angle effect becomes visible after range correction, thus demonstrat-
Fig. 10. Comparison of original and corrected intensities. Samples of (a) and (b) are from different regions of a white wall. The histograms of (c) and (d) are drawn from all samples combined. (a) Box chart of intensity before correction. (b) Box chart of intensity after correction. (c) Histogram of original intensity (before correction). (d) Histogram of intensity after correction.

VI. CONCLUSION

In this paper, the near-distance effect of TLS intensity data caused by range has been analyzed, and a corresponding correction method based on an estimation of the laser transmission function has been proposed. Experimental results show that the elimination of the range effect on TLS intensity data is possible. Using an existing incidence angle correction method, data from different material surfaces were corrected to visualize the effectiveness of this method. Since the interaction between the laser beam and the object surface is complex, further studies of intensity correction should focus on the scanning geometry of TLS, specifically the relationship between the effect of incidence angle and an object’s surface properties. In addition, this paper reveals that, when a laser beam is reflected by corner objects, the backscatter signal is stronger than normal and the measured range is larger than the actual value [as pointed out by the arrow in the middle of Fig. 9(e)]. These results require a more profound understanding of the TLS laser traverse mechanism, particularly the interaction between the laser beam and the geometry or shape of an object.

APPENDIX

LiDAR Equation: The LiDAR equation describes the relationship between emitted laser power $P_E$ and received laser power $P_R$, which is diminished by the sensor optics, object properties, and atmospheric transmission, as follows:

$$P_R = \frac{P_E D_R^2}{4\pi R^4} \sigma \eta_{Sys} \eta_{Atm} \xi.$$  \hspace{1cm} (A1)

In (A1), the term $D_R$ is the aperture diameter, $R$ is the range from sensor to target, $\beta_R$ is the laser beam width, $\eta_{Sys}$ is the...
system transmission factor, and \( \eta_{\text{Atm}} \) is the atmosphere transmission factor. The target cross section \( \sigma = \pi \rho R^2 \beta R \cos \alpha \) assumes that the object surface is larger than the circular laser footprint (extended object) and is a perfect Lambertian reflector with a solid angle of \( \pi \) steradians [13]. Then, (A1) can be simplified as

\[
P_R = \frac{P_E D_R^2 \rho \cos \alpha}{4R^2} \eta_{\text{Sys}} \eta_{\text{Atm}} \tag{A2}
\]

where \( \rho \) and \( \alpha \) denote the reflectance of the object surface and incidence angle, respectively [13], [26], [27]. For a specific close-range terrestrial laser scanner in a certain power mode (such as high power), \( P_E, D_R, \) and \( \eta_{\text{Sys}} \) are constant, and \( \eta_{\text{Atm}} \) is essentially 1 [13]. Therefore

\[
P_R = \frac{C_E \rho \cos \alpha}{R^2} \tag{A3}
\]

where the term \( C_E = (P_E D_R^2 \eta_{\text{Sys}} \eta_{\text{Atm}}) \) is a constant.

Near-Distance Effect: The laser beam generated by TLS is usually considered a Gaussian beam, and the power contained within the radius \( r \) perpendicular to the laser beam is given as

\[
P(r) = P(\infty) \left[ 1 - \exp\left( -\frac{2r^2}{w_0^2} \right) \right]. \tag{A4}
\]

Parameter \( w_0 \), usually called the Gaussian beam radius, is the radius at which the intensity decreases to \( 1/e^2 \) or 0.135 of its value on the axis. \( P(\infty) \) is a constant that denotes the total power of the incidence beam, which is also equal to \( P_R \) as defined in (A3).

The backscattered laser signal is focused on the detector placed along the optical axis at a fixed distance \( S_d \) from the lens. From [33], the lens formula for the Gaussian beam is

\[
\frac{1}{S_o} + \frac{1}{S_i} = \frac{1}{f}
\]

where \( S_o \) and \( S_i \) are the distances of the object and its image from the center of the lens with a focal length \( f \) and \( z_l = \pi w_0^2 / \lambda \) in which \( w_0 \) is the Gaussian beam radius at the smallest waist of the incidence beam.

To simplify the calculations, suppose \( w_0 = 0 \) and the divergence of the beam is \( \theta \). Thus, the Gaussian beam radius at distance \( z \) from the \( w_0 \) point is \( w(z) = z \tan \theta \), and the lens formula can be written as

\[
\frac{1}{S_i} = \frac{1}{f} - \frac{1}{S_o}. \tag{A6}
\]

After focusing of the lens, the divergence of the output beam is \( \tan \theta = D / S_i \), where \( D \) is the diameter of the lens. As \( z = S_i - S_d \), combining with (A6), at the detector plane, the Gaussian beam radius is

\[
w_d = w(z) = \left( \frac{S_i - S_d}{S_i} \right) \tan \theta = \frac{D(S_i - S_d)}{S_i} = D \left( 1 - \frac{S_d}{f} + \frac{S_d}{S_o} \right). \tag{A7}
\]

Assuming that the laser detector is circular and its radius is \( r_d \), a constant, then from (A4), the power received by the detector is

\[
P(r_d) = P(\infty) \left[ 1 - \exp\left( -\frac{2r_d^2}{w_d^2} \right) \right]. \tag{A8}
\]

Combining with (A7) and supposing that \( S_o = R + d \) in which \( d \) is the offset between the measured range \( R \) and object distance from the lens plane, the power received by the detector varies only with \( R \) as follows:

\[
P(R) = P(\infty) \left[ 1 - \exp\left( -\frac{2r_d^2(R + d + dS_d)}{w_d^2} \right) \right]. \tag{A9}
\]

Then, the ratio of the input laser signal captured by the detector is

\[
\eta(R) = \frac{P(R)}{P(\infty)} = 1 - \exp\left( -\frac{2r_d^2(R + d)}{w_d^2} \right). \tag{A10}
\]

Thus, combining with (A3), the intensity value for a coaxial TLS considering the near-distance effect is

\[
I(R, \alpha, \rho) \propto P(R, \alpha, \rho) = \eta(R) \frac{C_E \rho \cos \alpha}{R^2}. \tag{A11}
\]

In these formulas, if the detector is placed at the focus point \( (S_d = f) \), then (A10) can be written as

\[
\eta(R) = 1 - \exp\left( -\frac{2r_d^2(R + d)}{w_d^2} \right) \tag{A12}
\]

and a typical upside-down normal distribution. At close ranges, \( \eta(R) \) increases sharply as \( R \) increases; at far distances, \( \eta(R) \) remains almost at 1.0 and the shape of \( I(R, \alpha, \rho) \) becomes similar to \( K/R^2 \).

REFERENCES


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