RADIOMETRIC CALIBRATION OF FULL-WAVEFORM SMALL-FOOTPRINT AIRBORNE LASER SCANNERS

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ABSTRACT:

Small-footprint airborne laser scanners (ALS) are lidar instruments originally developed for topographic mapping. In recent years ALS sensors are increasingly used also in other applications (forest mapping, building extraction, power line modelling, etc.) and their technical capabilities are steadily improving. While the first ALS systems only allowed determining the range from the sensor to the target, current ALS sensors also record the amplitude of the backscattered echoes (peak power of the received echo), or even the complete echo waveform. To fully utilise the potential of the echo amplitude and waveform measurements in applications, it is necessary to perform a radiometric calibration. The calibration process involves the definition of the physical quantities describing the backscattering properties of objects and the development of practical calibration techniques. These issues are currently addressed by an EuroSDR (http://www.eurosdr.net/) project which aims at developing ALS calibration standards. This paper reviews the definition of common scattering (reflectance) parameters and concludes that in the case of small-footprint airborne laser scanning, the cross section σ [m^2] and the backscattering coefficient γ [m^2m^{-2}], which is defined as the cross section normalised with the cross-section of the beam hitting the larget, are the preferred quantities for describing the scattering properties. Hence, either σ or γ should be used in the calibration. Also, some results of converting full-waveform data acquired with the *RIEGL* LMS-Q560 to cross section data over urban and rural test sites in Austria are shown.

1. INTRODUCTION

Airborne laser scanners (ALS) designed for topographic mapping – also referred to as topographic lidar – transmit narrow-beam laser pulses with a high pulse repetition frequency and measure the round-trip time of the pulses travelling from the sensor to the ground and back (Wehr and Lohr, 1999). After converting the time measurements to range and precise geolocation, an irregular but dense 3D point cloud representing the scatterers is obtained. While first ALS systems only measured the round-trip time, more advanced systems also record the echo amplitude (peak power of the received echo, most commonly referred to as “intensity”) or the complete echo waveform (Wagner et al., 2004). In this way, not only information about the 3D location of the scatterers is collected, but also information about the physical backscattering characteristics. This opens the possibility for identifying target classes (e.g. vegetation, asphalt, or gravel) and target properties (size, reflectivity and orientation of scatterers). However, the echo amplitude and waveform measurements depend not only on the backscattering properties of the targets but also on sensor and flight parameters such as the flying altitude, beam divergence, laser pulse energy, atmospheric conditions, etc. (Hopkinson, 2007). Therefore, amplitude and waveform measurements from different sensors, acquisition campaigns and flight strips are not directly comparable. It may even not be possible to compare the measurements taken within one individual flight strip because of topographic height variations and variable atmospheric conditions along the flight path.

For segmentation and classification purposes it would in general be sufficient to perform a relative correction of the ALS amplitude and waveform measurements. Relative correction methods such as proposed by (Coren and Sterzai, 2006), (Ahokas et al., 2006) and (Höfle and Pfeifer, 2007) aim at reducing echo amplitude variations by correcting the measurements relative to some reference, e.g. relative to a reference range R_{ref}. However, it is much more desirable to convert the echo amplitude and waveform measurements into physical parameters describing the backscatter properties of the scatterers in a quantitative way. As pointed out by (Freeman, 1992) for the case of Synthetic Aperture Radar (SAR) imaging, this is because one would like to compare measurements from different sensors and/or flight strips, extract geophysical parameters from the backscatter measurements using models, carry out multi-temporal studies over large areas, and build up a database of backscatter measurements for different types of land cover and incidence angles.

To convert the sensor raw data into physical parameters it is necessary to apply calibration procedures. In remote sensing, calibration normally involves monitoring of sensor functions (internal calibration) and correction of the measurements with the help of known external reference targets (external calibration). Because current ALS instruments do not monitor sensors functions crucial for the radiometric calibration of the measurements (e.g. laser pulse energy), their calibration has yet to rely solely on external reference targets. First results using external reference targets have been presented by (Ahokas et al., 2006; Kaasalainen et al., 2005; Kaasalainen et al., 2008;

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Wagner et al., 2006), yet many issues require further clarification.

One unresolved problem is that there is not yet a consensus on the definition and usage of the involved radiometric and reflectance quantities. For example, the echo amplitude recorded by topographic lidars is most commonly referred to as "intensity" despite the fact that in physical terms it would be more natural to associate the intensity with the total energy of one echo, while the amplitude measurement only characterises the peak power of the echo. Also, terms like "reflectivity", "reflectance", or "backscatter" are often used synonymously without providing a clear definition of their meaning.

In this paper we firstly review some definitions of physical quantities used for describing the scattering of radiation by objects (Section 2). Then we discuss approaches for the radiometric calibration of full-waveform ALS data using external reference targets (Section 3) and show some results of case studies carried out with full-waveform data acquired with the *RIEGL* LMS-Q560 (Section 4).

2. SCATTERING THEORIES

2.1 Biconical Reflectance

The scattering (reflectance) theory as commonly employed by the remote sensing community in the visible and infrared portion of the electromagnetic spectrum was introduced by (Nicodemus et al., 1977) (Schaepman-Strub et al., 2006). The basic quantity of this theory is the bidirectional reflectance distribution function f (BRDF) [sr^{-1}] defined by

$$f(\theta_i,\phi_i;\theta_s,\phi_s)=\frac{L_s(\theta_i,\phi_i;\theta_s,\phi_s)}{E_i(\theta_i,\phi_i)} \tag{1}$$

where L_s is the scattered (reflected) radiance, E_i is the irradiance, and θ and ϕ are the zenith and azimuth angles. The subscripts i and s refer to the incident and scattered radiation respectively. The radiance L [$Wm^{-2}sr^{-1}$] is defined as

$$L=\frac{d^2P}{\cos\theta\cdot dA\cdot d\Omega} \tag{2}$$

where d2P is the radiant flux [W] through an area dA in the direction (θ, ϕ) within the cone dΩ. The irradiance E [Wm-2] is

$$E=\frac{dP}{dA} \tag{3}$$

Thus, the BRDF can be expressed in terms of the incident and scattered power:

$$f(\theta_i,\phi_i;\theta_s,\phi_s)=\frac{d^2P_s}{\cos\theta_s\cdot dP_i\cdot d\Omega_s} \tag{4}$$

Being the ratio of infinitesimal quantities, the BRDF cannot be measured (Schaepman-Strub et al., 2006). Real measurements always involve an average of f over finite intervals, e.g. over the solid angle Ω. It should also be noted that Equation (1) assumes monochromatic, uniform, and isotropic (L is constant, independent of θ and ϕ) illumination and does not treat interference, diffraction, transmission, absorption, fluorescence, and polarisation effects (Kavaya et al., 1983).

In lidar applications the basic measurable quantity is the biconical reflectance ρ defined as the ratio of the scattered radiant flux P_s in the direction (θ_s, ϕ_s) within the cone Ω_s to the incident flux P_i in the direction (θ_i, ϕ_i) within Ω_i (Kavaya et al., 1983):

$$\rho(\Omega_i,\Omega_s)=\frac{P_s(\theta_s,\phi_s;\Omega_s)}{P_i(\theta_i,\phi_i;\Omega_i)} \tag{5}$$

Due to the quasi collinear backscatter geometry $\theta_s \cong \theta_i$ and $\phi_s \cong \phi_i+\pi$. Considering that in ALS the solid angles of both the illuminating and received radiation are typically small, the biconical reflectance can be written as:

$$\rho(\Omega_i,\Omega_s)=\langle f(\theta,\phi;\theta,\phi+\pi)\rangle\Omega_s\cos\theta_s \tag{6}$$

where the brackets 〈〉 indicate the average over the finite solid angle intervals Ω_i and Ω_s.

2.2 Cross Section

In radar remote sensing one deals with coherent radiation which requires that scattering phenomena are described using the laws of electrodynamics. In electrodynamics the basic quantity to describe the scattering of a wave by an object is the cross section σ [m^2] customarily defined by (Jackson, 1983)

$$\sigma=\lim_{R\to\infty}4\pi R^2\frac{\langle \mathbf{E}_s\cdot\mathbf{E}_s^*\rangle}{|\mathbf{E}_i|^2} \tag{7}$$

where R is the distance to the target, $\mathbf{E}_i$ and $\mathbf{E}_s$ are the incident and scattered electric field vectors respectively, the brackets 〈〉 denote the ensemble average (for the case of rough targets), * is the symbol for the complex conjugate, and | | is the absolute value. The incoming wave $\mathbf{E}_i$ is usually assumed to be a plane wave travelling along the direction (θ_i, ϕ_i). The scattered field $\mathbf{E}_s$ is found by considering the boundary conditions imposed by the target (geometry and dielectric properties).

In radar remote sensing of the earth's surface the target is larger than the resolution cell of the radar system. In such a situation it is advantageous to introduce the cross-section per unit-illuminated area [m^2m^{-2}] (Ulaby et al., 1982):

$$\sigma^0=\frac{\sigma}{A_i} \tag{8}$$

where A_i is the illuminated surface area. The use of σ^0 has the advantage that measurements of radar systems with different resolution can be more readily compared, while σ increases in general with A_i. However, when the incidence angle of the radar beam on a given surface is changed, the illuminated area A_i is also changed. Therefore it might be more convenient to relate the scattering strength to the cross-section of the incoming beam, $A_i\cos\theta_i$, instead of the illuminated target area A_i (Schanda, 1986):

$$\gamma = \frac{\sigma}{A_i \cos\theta_i} \tag{9}$$

where γ is the bistatic scattering coefficient [m^2m^{-2}].

The cross section can be related to the biconical reflectance ρ and the BRDF by considering the relation (Leader, 1979):

$$\frac{P_s}{P_i} = \frac{A_r\left\langle E_s E_s^* \right\rangle}{A_i \cos\theta_i \left|E_i\right|^2} = \rho(\Omega_i, \Omega_s) \tag{10}$$

where A_r is the effective receiver aperture area. Recognising that

$$\Omega_s = \frac{A_r}{R^2} \tag{11}$$

one obtains for the cross section σ following relationships:

$$\sigma = \frac{4\pi}{\Omega_s}\rho(\Omega_i, \Omega_s) A_i \cos\theta_i \tag{12}$$

$$\sigma = 4\pi \left\langle f \right\rangle A_i \cos\theta_i \cos\theta_s \tag{13}$$

Correspondingly, the relationships for the area-normalised cross section σ^0 and the bistatic scattering coefficient γ are:

$$\sigma^0 = \frac{4\pi}{\Omega_s}\rho(\Omega_i, \Omega_s)\cos\theta_i \tag{14}$$

$$\sigma^0 = 4\pi \left\langle f \right\rangle \cos\theta_i \cos\theta_s \tag{15}$$

$$\gamma = \frac{4\pi}{\Omega_s}\rho(\Omega_i, \Omega_s) \tag{16}$$

$$\gamma = 4\pi \left\langle f \right\rangle \cos\theta_s \tag{17}$$

In backscattering geometry ($\theta_s = \theta_i = \theta$) σ^0 respectively γ are usually called "backscattering coefficient" and are expressed in decibel.

2.3 Lambertian Scatterer

A perfectly diffuse or Lambertian surface is one for which the reflected radiance is isotropic so that L_s is a constant, with the same value for all scattering directions (θ_s, ϕ_s), regardless of how it is irradiated (Nicodemus et al., 1977). For such surfaces there is a simple relationship between the diffuse BRDF, f_d, and the diffuse reflectance, ρ_d, defined as the fraction of the total incident flux that is reflected in all directions into the full hemisphere (2π) above the scattering surface A:

$$\rho_d = \frac{P_s(2\pi)}{P_i} = \frac{\int_{2\pi} L_{s,d} A \cos\theta_s d\Omega_s}{E_i A} \tag{18}$$

$$\rho_d = \frac{L_{s,d}}{E_i}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \cos\theta_s \sin\theta_s d\theta_s d\phi_s \tag{19}$$

hence

$$f_d = \frac{\rho_d}{\pi} \tag{20}$$

The diffuse reflectance is also often referred to as reflectivity or albedo. For the collinear backscatter geometry in ALS, the cross section and backscattering coefficients of a Lambertian surface thus become:

$$\sigma = 4\rho_d A_i \cos^2\theta \tag{21}$$

$$\sigma^0 = 4\rho_d \cos^2\theta \tag{22}$$

$$\gamma = 4\rho_d \cos\theta \tag{23}$$

3. CALIBRATION

In radar remote sensing the calibration is performed based on the radar equation which gives the received power as a function of sensor parameters, measurement geometry and the scattering properties of the target. For the lidar case, the radar equation can be derived starting from equations (5) and (12):

$$P_s = P_i \rho(\Omega_i, \Omega_s) = P_i \frac{\Omega_s}{4\pi A_i \cos\theta_i}\sigma \tag{24}$$

Assuming circular transmitter and receiver apertures, one can replace Ω_s and $A_i\cos\theta_i$ by

$$\Omega_s = \frac{\pi D_r^2}{4R^2} \tag{25}$$

$$A_i \cos\theta_i = \frac{\pi(R\beta_t)^2}{4} \tag{26}$$

where D_r is the diameter of the receiver aperture and β_t is the transmitter beamwidth. By substituting Equations (26) and (27) into Equation (24) one arrives at the following formulation of the radar equation:

$$P_s = \frac{P_i D_r^2}{4\pi R^4 \beta_t^2}\sigma \tag{27}$$

Starting from this equation, (Wagner et al., 2006) showed that the backscatter cross section of an individual target can be derived from ALS measurements from following calibration equation

$$\sigma = C_{Cal} R^4 \hat{p} s_p \tag{28}$$

where C_{Cal} is a calibration constant, R is the range from the sensor to target, $\hat{p}$ is the echo amplitude and s_p is the echo width. While the echo amplitude is recorded by most current ALS systems, the echo width is only available from full-waveform digitising ALS sensors. Also, it is often not known how non-linear effects of the ALS receiving units are corrected for. Therefore only full-waveform ALS sensors allow an accurate calibration for all target classes. With conventional ALS systems one has to assume that s_p is constant for all targets and that the echo amplitude is linearly related to the peak power of the echo.

Using Equation (28) the radiometric calibration can be performed using external reference targets of known cross section. Due to the lack of better alternatives, (Wagner et al., 2006) used an asphalt road for calibration, assuming that the road behaves as a Lambertian scatterer with ρ_d = 0.2. A more accurate calibration can be achieved using manufactured reference targets such as the 5 × 5 m tarps used by (Ahokas et al., 2006; Kaasalainen et al., 2005; Kaasalainen et al., 2008), or by using natural reference targets where the cross section has been determined in the field (Briese et al., 2008).

Instead of using σ one may also consider using the backscattering coefficient γ

$$\gamma = \frac{C_{Cal} R^4 \hat{p} s_p}{A_1 \cos\theta_1} = \frac{4 C_{Cal} R^2 \hat{p} s_p}{\pi \beta_t^2} = C'_{Cal} R^2 \hat{p} s_p \tag{29}$$

which would facilitate the comparison of the scattering characteristics of area-extensive targets (one echo per laser shot) across different sensor and flight parameters due to the normalisation with $A_i\cos\theta_i$. At the same time, the scattering properties of small targets (multiple echoes per laser shot), which have the same σ for any A_i as long as their scattering area is smaller than $A_i\cos\theta_i$, would become less comparable. Nevertheless, given that except over vegetation, single echo measurements represent the dominant majority of cases in small-footprint ALS, it might be advantageous to use γ instead of σ.

Other alternatives have more severe caveats. In the case of σ^0 the problem is that the $\cos\theta$ term appears in the calibration equation

$$\sigma^0 = C'_{Cal} R^2 \hat{p} s_p \cos\theta \tag{30}$$

Because significant processing and modeling is necessary to estimate the local incidence angle θ for each echo (e.g. echoes from tilted surfaces), it is not as straight forward to calculate as σ or γ. Therefore the use of σ^0, which is the most widely used parameter in radar remote sensing, is not recommended in small-footprint ALS.

A major disadvantage of the various reflectance terms discussed before is that they lack the theoretical foundation as given for the cross section and its derivates (Equation 7). In addition, as one can see from Equation (31), the $\cos\theta$ term also appears in the equation for the BDRF and so the same argument as for σ^0 applies:

$$\langle f \rangle = \frac{C'_{Cal} R^2 \hat{p} s_p}{4\pi \cos\theta} \tag{31}$$

The biconical reflectance $\rho(\Omega_i, \Omega_s)$ is unattractive because it is highly dependent on the sensor and flight parameter due to its definition (Equation 5). Finally, the use of the diffuse reflectance ρ_d is problematic because many surfaces can be expected to show an anisotropic scattering behaviour.

4. CASE STUDIES

Full-waveform measurements acquired over urban and rural test areas in Austria using the *RIEGL* LMS-Q560 have already been used in several studies to derive the backscatter cross section σ. The method was introduced in (Wagner et al., 2006) and later applied to study the characteristics of lidar backscatter of vegetation and terrain (Wagner et al., 2008) and to improve the quality of terrain models obtained by filtering the ALS derived 3D point cloud (Doneus et al., 2008; Ullrich et al., 2007; Ullrich et al., 2008; Wagner et al., 2008). In these first studies the LMS-Q560 data were calibrated by using asphalt roads as reference targets and by assuming the selected asphalt areas behave like Lambertian scatterers with a diffuse reflectance of ρ_d = 0.2. As an improvement to this approach (Wagner et al., 2008) used a portable laser reflectometer and Spectralon® targets for an improved characterisation of the reflectance of the asphalt area used for the calibration. It was found that ρ_d = 0.25. In addition, (Briese et al., 2008) added an atmospheric correction term to consider present atmospheric conditions during data acquisition, which is advantageous if multi-temporal data acquired under different atmospheric conditions are compared.

Figure 1 show exemplary σ images over vegetated and built-up terrain respectively and compare them to orthophotos of the same areas. The full-waveform ALS data were acquired in 2005 over the area of the Schönbrunn Palace in Vienna by the company Milan-Flug GmbH. The flight and scan settings used for this campaign provide an approximate mean point density of four measurements per square meter.

(a) vegetated terrain (b) built-up terrain

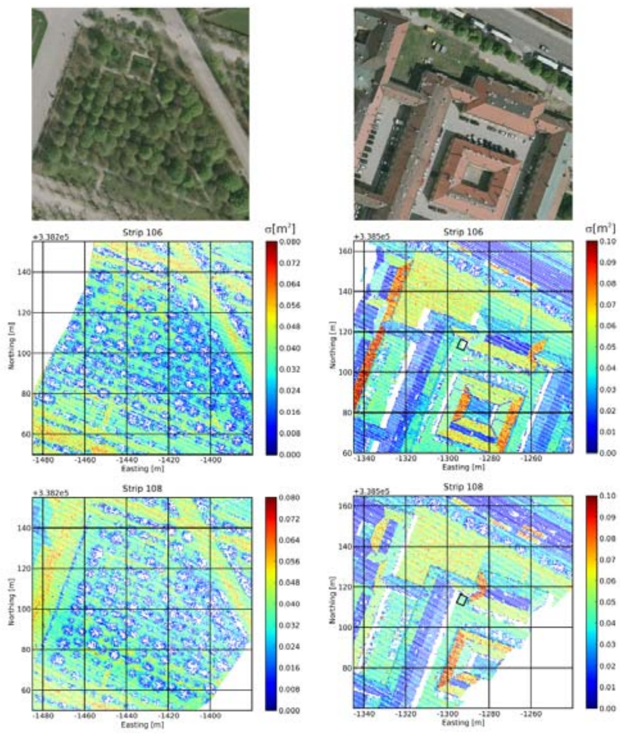

Fig. 1. Images of the backscatter cross section σ for a vegetated (left) and built-up area (right) for two different flight strips. The reference area used for the radiometric correction is highlighted by a rectangle.

Notice that the scale of the colour table in the two columns of figure 1 is different. Within vegetation the laser beam frequently hits several scatters like leaves and branches before reaching the trunk or the ground which causes a series of echoes per shot and a reduced illuminated area contributing to each echo. This results in significantly lower amplitudes and therefore also lower backscatter cross sections in these areas (Wagner et al., 2008).

In both test scenes it can be seen that the backscatter cross section calculated from both flight strips is quite similar for non- or only modestly tilted areas. High σ values can be found in regions covered with gravels, flagstones, or grass. Asphalt typically has low backscatter values. Inclined flat surfaces like roofs with a normal vector pointing towards to the ALS sensor have higher σ values while surfaces with a normal vector pointing away from the sensor have significant lower σ values. This fact demonstrates the significant influence of the incidence angle on the radiometric ALS measurements.

5. CONCLUSIONS

The latest generation of small-footprint airborne laser scanners (ALS) measure, in addition to the range, also the echo amplitude (commonly referred to as "intensity") or the complete waveform of the backscattered echo. These measurements allow distinguishing different target classes and are expected to be a valuable for geophysical parameter retrieval techniques. However, before this potential can be realised, the amplitude and waveform measurements must be calibrated. While relative calibration techniques may suffice for non-physically based segmentation and classification purposes, more advanced methods involving physical models require an absolute calibration of the measurements.

The absolute calibration of the ALS amplitude and waveform measurements can be achieved using external reference targets with known backscattering characteristics. Because the backscattering characteristics may be characterised using different physical quantities (BRDF, biconical reflectance, diffuse reflectance, cross section, backscatter coefficient, etc.) it is important to agree on standards and to be clear on how the calibration was performed. As highlighted by (Schaepman-Strub et al., 2006) for the case of optical imaging techniques, the lack of standardisation of reflectance terminology and products has become a considerable source of error. They therefore suggested to standardise the terminology in reflectance product descriptions following the theoretical framework introduced by (Nicodemus et al., 1977).

In this paper we argue based on theoretical considerations that in the case small-footprint airborne laser scanning, the cross section σ [m^2] and the backscattering coefficient γ [m^2m^{-2}], which is defined as the cross section normalised with the cross-section of the incoming beam, are the preferred quantities for describing the scattering properties and hence should be used in the calibration. Further experimental work is required to find practical calibration procedures for deriving σ and γ and to characterise their error bars.

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