ISPRS Journal of Photogrammetry and Remote Sensing 65 (2010) 505–513

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Radiometric calibration of small-footprint full-waveform airborne laser scanner measurements: Basic physical concepts

Wolfgang Wagner *

Christian Doppler Laboratory for Spatial Data from Laser Scanning and Remote Sensing, Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Gusshausstrasse 27-29, 1040 Vienna, Austria

ARTICLE INFO

Article history:
Received 19 March 2010
Received in revised form
28 May 2010
Accepted 22 June 2010
Available online 15 September 2010

Keywords:
Laser scanning
Lidar
Calibration
Cross section
Backscatter coefficient

ABSTRACT

Small-footprint (0.2–2 m) airborne laser scanners are lidar instruments originally developed for topographic mapping. While the first airborne laser scanners only allowed determining the range from the sensor to the target, the latest sensor generation records the complete echo waveform. The waveform provides important information about the backscattering properties of the observed targets and may be useful for geophysical parameter retrieval and advanced geometric modelling. However, to fully utilise the potential of the waveform measurements in applications, it is necessary to perform a radiometric calibration. As there are not yet calibration standards, this paper reviews some basic physical concepts commonly used by the remote sensing community for modelling scattering and reflection processes. Based purely on theoretical arguments it is recommended to use the backscattering coefficient γ, which is the backscatter cross-section normalised relative to the laser footprint area, for the radiometric calibration of small-footprint full-waveform airborne laser scanners. The presented concepts are, with some limitations, also applicable to conventional airborne laser scanners that measure the range and intensity of multiple echoes.

1. Introduction

Airborne laser scanning (ALS) instruments operate on the same principle as radar (radio detection and ranging) instruments by sending out short laser pulses and measuring the time delay of the backscattered echoes for range determination (Jenn, 2005). Therefore the acronym lidar (light detection and ranging) is also often used. Like side-looking radars, ALS sensors can record the strength of the backscattered echoes for constructing images of the surveyed area. Indeed, such sensors have increasingly become available in recent years, but there are not yet standards for radiometric calibration. In some cases it is even not quite clear what these instruments record. For example, some ALS sensors are capable of registering the time delay of multiple echoes for each transmitted laser pulse, but only one intensity value representing the peak power of the complete return signal (Jensen, 2007). Therefore, it is not possible to assign the intensity value to a specific target if two or more echoes are detected. Other ALS instruments are capable of recording the peak power of all recorded echoes. But because echoes may overlap and have different widths, it is not possible to estimate the energy of each echo just based on these peak measurements. The echo energy, however, is required for a proper radiometric calibration of the ALS measurements.

Despite these technical limitations, ALS intensity data have already proven to be very useful for classification purposes (Antonarakis et al., 2008; Chust et al., 2008; Holmgren and Persson, 2004; Rottensteiner et al., 2005). Also correction techniques to adjust intensity variations due to the influence of variable flying altitude, topography and atmospheric conditions are already available (Coren and Sterzai, 2006; Höfle and Pfeifer, 2007; Hopkinson, 2007; Kaasalainen et al., 2005). These studies point to the high information content of ALS intensity measurements, but in order to reach calibration standards as common in radar remote sensing it is necessary to record the complete return signal rather than just peak power measurements.

Airborne laser scanners capable of digitising the complete echo signal are known as full-waveform sensors, whereas the term "waveform" refers to the shape of the return signal (Mallet and Bretar, 2009). Waveform-digitising sensors have long been used in bathymetry because the complex echoes from coastal waters do not permit one to reliably calculate seafloor depth in real time during data acquisition (Guenther et al., 2000; Wozencraft and Millar, 2005). Precise depths are determined via post-flight processing of stored waveforms. Also large-footprint lidar systems such as the airborne Laser Vegetation Imaging Sensor (LVIS) (Blair et al., 1999) or the Geoscience Laser Altimeter System (GLAS)

* Tel.: +43 1 58801 12225.
E-mail address: ww@ipf.tuwien.ac.at.

0924-2716/$ – see front matter © 2010 International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS). Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.isprsjprs.2010.06.007

flown on-board the ICESat satellite (Zwally et al., 2002) have waveform-digitising capabilities. These waveform measurements have proven useful for a diverse range of applications such as monitoring the elevation of sea ice above the sea level (Kurtz et al., 2008) or mapping the vertical structure of forests (Sun et al., 2008). However, these studies have in general only exploited the relative distribution of backscatter energy over the waveforms. Only few studies have yet considered the absolute radiometric calibration of these large-footprint measurements (Lancaster et al., 2005).

Another type of full-waveform laser scanners is small-footprint systems designed primarily for topographic mapping and other terrestrial applications (Mallet and Bretar, 2009). Instruments from three manufacturers became available in 2004 (Persson et al., 2005; Wagner et al., 2004), but as in the case of bathymetric and large-footprint lidar systems, the possibility of performing an absolute radiometric calibration of the waveform measurements had initially not been conceived. The decomposition of the small-footprint waveforms into individual echoes allows one to estimate – in addition to the range – the amplitude and width of each echo (Chauve et al., 2007; Roncat et al., 2008a). These waveform attributes have already been found useful for segmenting ALS point clouds in city areas (Melzer, 2007), tree classification (Reitberger et al., 2008; Rutzinger et al., 2008), and separating terrain echoes from echoes scattered by bushes and other low vegetation (Doneus et al., 2008; Lin and Mills, 2010; Wagner et al., 2008a). This latter capability is important for improving the quality of terrain models because filtering techniques based purely on the geometric arrangement of the 3D point cloud may misclassify echoes from shrub canopies as terrain echoes (Riaño et al., 2007).

All these studies have demonstrated the high information content of ALS waveform measurements. Yet, without a proper radiometric calibration, waveform data acquired by different sensors and/or during different flight campaigns cannot be directly compared. Thus, any scientific method obtained from the study of uncalibrated waveform measurements lacks generality, i.e. it is questionable if it is applicable to other experimental data sets as well. Also, without neither knowing the physical units of these measurements nor their associated error ranges, it is in a strict sense impossible to link physical theory and experimental observations. As a contribution to the on-going debate about potential standards for the radiometric calibration of small-footprint full-waveform ALS measurements, this paper reviews basic physical concepts and suggests adopting calibration standards as common in radar remote sensing. This paper extends and completes initial discussions published by Wagner et al. (2008b).

2. Radiometric calibration

Radiometric calibration refers to the process of deriving physically well-defined radiometric quantities from the sensor's raw measurements. It is one of the first steps within any remote sensing data processing chain that transforms unprocessed instrument and payload data at full resolution (Level 0) stepwise to geometrically corrected data in sensor units (Level 1), geophysical variables at the same resolution and location (Level 2), and finally value-added data products mapped on uniform space–time grid scales (Level 3 and Level 4) (Parkinson et al., 2006). It is thus clear that a proper radiometric calibration is essential if sensor intensity measurements are to be used for the retrieval of higher level data products and subsequently in different applications.

Radiometric calibration methods differ from one remote sensing technique to the other (de Vries et al., 2007; Freeman, 1992; Honkavaara et al., 2009; Kaasalainen et al., 2009), but the basic principles are the same, independent of the remote sensing technique being considered. The first step in any calibration is to identify a theoretical framework that allows one to describe the measurement process with the desired accuracy. This is not as straightforward as one might expect because there are typically several physical theories that may be suited for this task. The crucial question to be asked is whether the theory is general enough to describe all the physical phenomena observed by the remote sensing instrument (Shapiro, 1982), while being simple enough to be applicable in real-world applications? Once a proper theoretical framework has been identified it is then possible to set up a model that links the sensor output to the desired physical quantity taking the different instrument parameters into account.

The final step is to find practical procedures for the calibration of the instruments. As discussed by Dinguirard and Slater (1999) for the case of optical sensors, this may involve three types of calibration, namely, pre-flight, on-board and vicarious calibration. Ideally, several different and independent calibration techniques should be used to determine if systematic errors exist in one or more of these techniques. Pre-flight calibration is usually done based on laboratory measurements of standard reference targets such as calibration spheres or Lambertian reflectors (Ames et al., 2005). On-board calibration may involve the monitoring of internal sensor functions and taking regular measurements of artificial and/or stable natural targets. Examples are the on-board calibration of thermal infrared measurements using hot (internal) and cold (deep-space) calibration sources (Trishchenko and Li, 2001) and the calibration of spaceborne radars using ground-based active transponders (Verspeek et al., 2010). Finally, vicarious calibration is usually done by monitoring pseudo-invariant natural targets like the White Sands Missile Range high-reflectance alkali flats in the case of optical sensors (Biggar et al., 2003) or a tropical forest in the case of radar instruments (Lecomte and Wagner, 1998). However, more indirect approaches such as the comparison of Level 1 and 2 data with independent model predictions have also been exploited for vicarious calibration (Lancaster et al., 2005; Verspeek et al., 2010).

Following the logic outline above, this paper firstly reviews scattering theories suitable for describing scattering processes as observed by small-footprint full-waveform laser scanners (Section 3). This leads then to the formulation of the radar equation which can be used for deriving a waveform calibration model (Section 4). Finally, Section 5 discusses potential methods for pre-flight, on-board and vicarious calibration.

3. Scattering theories

3.1. Radiative transfer- versus electromagnetic theory

Because light scattering has traditionally been a separate discipline from radar scattering, there is unfortunately a separate notion and terminology in the two communities (Jenn, 2005). This historical separation continues to reverberate in the ALS community that still needs to agree on which terminology shall be used for full-waveform calibration. This question is not only a matter of mere nomenclature, but touches on the fundamental question which physical phenomena shall be observed and modelled? In optical remote sensing, light propagation and reflection are typically described within the framework of the radiative transfer theory (Chandrasekhar, 1950) which is a heuristic theory only concerned with geometrical (ray) optics and incoherent light, i.e. it is assumed that the addition of powers rather than the addition of fields hold (Ishimaru, 1997). Therefore, radiative transfer theory does not allow treating wave phenomena such as interference, diffraction, etc. in a physically rigorous manner. Essentially, the description of reflectance of light by objects is thus reduced to a geometric problem which considers the geometric arrangement of the light source, the reflecting surface and the detector. On the basis of these assumptions Nicodemus et al. (1977) defined a widely cited, unified approach