

Radiometric Calibration of LIDAR Intensity With Commercially Available Reference Targets

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Abstract—We present a new approach for radiometric calibration of light detection and ranging (LIDAR) intensity data and demonstrate an application of this method to natural targets. The method is based on 1) using commercially available sand and gravel as reference targets and 2) the calibration of these reference targets in the laboratory conditions to know their backscatter properties. We have investigated the target properties crucial for accurate and consistent reflectance calibration and present a set of ideal targets easily available for calibration purposes. The first results from LIDAR-based brightness measurement of grass and sand show that the gravel-based calibration approach works in practice, is cost effective, and produces statistically meaningful results: Comparison of results from two separate airborne laser scanning campaigns shows that the relative calibration produces repeatable reflectance values.

Index Terms—Calibration, laser measurements, laser radar, laser radiation effects, remote sensing.

I. INTRODUCTION

RANGE measurements with airborne laser scanners have been developed and studied for two decades [1] with an increasing number of applications to environmental sciences [2]–[4]. Recently, environmental applications of terrestrial laser scanning have also been introduced [5]. Among the latest advances in laser scanning study is the calibration and more effective usage of the intensity information recorded by most laser scanners [6]–[8]. Thus far, the uncalibrated airborne laser scanning (ALS) intensity data have mainly been used for target classification purposes of, e.g., trees and vegetation [9],

[10] or snow in glaciers [11] but practical demonstrations of radiometric (brightness) calibration are still scarce, and the intensity has often been investigated rather by integration to other sensors, such as aerial imagery [12], [13]. There is also a growing interest in light detection and ranging (LIDAR) range data combined with hyperspectral reflectance for faster and more accurate classification of, e.g., forest parameters [14]. The availability of calibrated laser-based reflectance values would be significant with respect to automatic classification and data processing, and it would also solve some practical problems related to the combination of separate ALS data sets. There are also applications where separate aerial imaging flights would not be needed if calibrated intensity values from laser scanning were available, which would reduce the costs of airborne campaigns. Since ALS is increasingly being applied in countrywide data collection, calibrated intensity would provide another data set to be used in the future studies of global change.

In this paper, we investigate the calibration of intensity as the ratio of received power from the target to that received from a reference sample measured similarly to the target. The radar equation defines the power entering the receiver as [3]

$$P_r = \frac{P_t D_r^2}{4\pi R^4 \beta_t^2} \sigma \quad (1)$$

where P_t is the transmitted power, D_r is the receiver aperture, R is the range, and β_t is the transmitter beamwidth. The backscatter coefficient σ depends on the scattering solid angle Ω , the receiving area of the scatterer A_s , and the reflectivity ρ

$$\sigma = \frac{4\pi}{\Omega} \rho A_s. \quad (2)$$

There are some variations in the definition and usage of the terms “intensity,” “reflectance,” and “brightness,” particularly between different fields of environmental study that apply the physics of radiation in the interpretation of data. In laser scanning, the term intensity often represents the momentarily received power of the backscattered pulse. In this paper, the term reflectance is used as the laser power calibrated with that of a similarly measured reflectance standard and most closely represents the *reflectance factor*, which is defined as the ratio of the reflectance of the surface to that of a perfectly diffuse (Lambert) surface measured in similar conditions of illumination and geometry [15]. Although it is practically impossible to find a perfect Lambert reference for ALS applications (because of both the limitations set by the measurement geometry [7], [16] and the requirements of the field use of these targets), it is

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TABLE I
SUMMARY OF THE LASER SCANNER FLIGHT CAMPAIGNS

Location & Date	Scanner	Altitude (m)	Targets (Approx. no. of points)
Nuuksio May 2006	Optech	1000	Greens (500-3000)
	ALTM	3100	Bunkers (50-400)
Espoonl. Dec 2006	TopEye Mk-II	300	Gravels (test set) (20-40)
Nuuksio Jul 2007	Leica ALS50	450	Gravels (20) Greens (800-1600) Bunkers (400-800)

The laser wavelength was 1064nm in all campaigns. The TopEye instrument recorded the entire waveform.

possible to normalize the reflectances of the field standards in a laboratory using a practically Lambertian standard. The recent international effort and projects related to the ALS intensity calibration concept are likely to bring many new insights into the technology and physics of LIDAR intensity measurement in the near future.

The development of the ALS intensity calibration concept demonstrated in this paper started in 2005 with the use of custom made brightness tarps, which could be used as reference targets in the flight area. This kind of approach has been first applied in the radiometric calibration of digital aerial images (e.g., [17]), and the first results of their usage in laser scanning were presented in [18] and [19]. The major drawbacks in using tarps as references are the high cost and limitations in availability if replacement is needed because of changes in the surface (caused by, e.g., surface impurity and weathering effects) [19], which lead to the search and investigation of low-cost, easily available, and transportable targets, allowing the use of the calibration method more widely. In this paper, we introduce a new approach for using reference targets based on commercially available sand and gravel instead of custom-made tarps. We concentrate on calibrating flat surfaces using non-waveform ALS data, whereas for distributed targets, such as forests, and for exact laser calibration, the full waveform capability may be needed in the future. The basic hypothesis of the study is that the received intensity after radiometric calibration describes target backscattering properties at least for flat surfaces. We also present the first practical demonstration and test of the reference target-based calibration method for natural ALS land targets and evaluate the reliability of these results. This paper is arranged as follows. The details of the ALS campaigns and laboratory measurements are presented in Section II including a description of samples and land targets. Section III presents the results from the initial test measurements and campaigns to find the most suitable samples for calibration and the results from the ALS flight campaigns where these samples were further investigated and applied in the calibration of land targets. The conclusion is in Section IV.

II. MEASUREMENT CAMPAIGNS AND EXPERIMENTS

A. ALS Campaigns

Airborne laser scanner data from three different flight campaigns and instruments are studied in this paper. The flight parameters and targets are summarized in Table I.

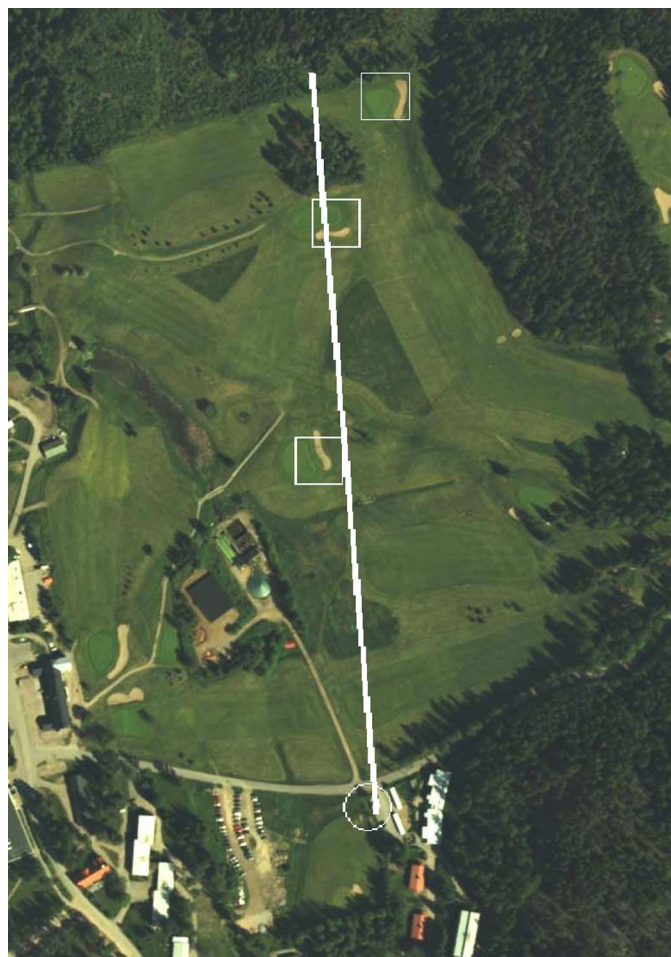


Fig. 1. Nuuksio July 2007 flight line over the Lakisto golf course (marked with a straight white line). The calibration gravel targets were placed inside the white circle, and the white squares denote the greens and bunkers, for which the intensity was measured and calibrated.

The first test campaign with a preliminary set of gravel and natural test targets occurred in the Espoonlahti December 2006 campaign with a TopEye MK-II 1064-nm laser scanner. The flight altitude was 300 m, and the test area consisted of the Espoonlahti boat harbor and beach (see [7] and [19] for more details on the target site and campaign).

Another set of gravel was measured during the Nuuksio July 2007 flights with Leica ALS50-II at a 450-m flight altitude. The location of the gravel targets in the premises of the Lakisto golf course provided us with an ideal opportunity for testing the calibration method with simple natural targets chosen from the golf course: putting greens and sand bunkers, which should be relatively homogeneous in quality and surface properties. The location of the reference targets as well as the measured greens and bunkers are seen in the aerial image of the test site, taken simultaneously with the laser flights (Fig. 1).

For comparison, data from greens and bunkers (from Master Golf course located in the area) are also included from the Nuuksio flight campaign on May 14–15, 2006. The data were acquired at an altitude of 1000 m with the Optech ALTM 3100 laser scanner. In this campaign, portable tarps were used for intensity calibration and provided a reference for usage and comparison of the brightness data [19].

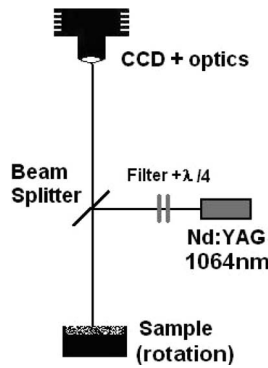


Fig. 2. Laboratory reference measurement setup, showing the backscatter geometry achieved with the beam splitter.

The effect of the range of each ALS survey was compensated to reference height assuming an R^2 relationship with the received power and the range to guarantee that measurements taken from different ranges were comparable, i.e., the laser beam was assumed to cover a number of individual scatterers.

B. Terrestrial Laser Scanner

To provide controlled laboratory reference measurements and investigate the problems and challenges related to the reflectance measurement carried out with a scanning (range) instrument, we measured the intensities of all targets with the 785-nm FARO LS 880HE80 terrestrial laser scanner (TLS). The scanner uses a phase modulation technique for the distance measurement with the accuracy of 3–5 mm and $360^\circ \times 320^\circ$ field of view. Additional corrections to the intensity values had to be applied because of the nonlinearity of the detector brightness scale (see [7] for more details on these corrections), since the detector of the scanner is not optimized for intensity measurement. To produce a consistent intensity calibration, all FARO measurements were carried out from a 1-m distance.

C. Laboratory Reference Measurements

The laboratory reference measurements were carried out to provide calibrated reference values for the reflectance of commercial and natural targets and to compare the consistency of the reflectances measured with different techniques, which is important for a calibration target to produce reliable results. The instruments used in the optical studies of backscatter commonly use beam splitter-based techniques to produce the 0° viewing geometry, where the light paths of the source and detector coincide (see [20] and references therein). Airborne laser scanners operate at backscatter geometry, because the long distance of the target (relative to that between the source and detector) causes the source–target–detector angle to be practically 0° . The laboratory experiment in this study (see Fig. 2 for an illustration) was based on the standard technique for backscatter measurements and has been described in detail in many of our previous articles (e.g., [7] and [16]). The instrument consists of a 10-mW 1064-nm Nd:YAG (neodymium yttrium aluminum garnet) laser, a 16-b monochrome digital camera (Sbig ST-7 CCD), and a near-infrared beam splitter to work out the backscatter geometry, i.e., the laser beam is first reflected into

the sample by the beam splitter, and the retroreflected intensity is observed through the beam splitter with the charge-coupled device (CCD) detector placed above the beam splitter and sample. To decrease the effect of laser speckle and allow a larger area of the sample to be illuminated (and hence reduce the deviation in data), the samples were placed on a rotator allowing the laser spot to move around the sample surface during the camera exposures. The high output power of the laser source required a neutral density filter in front of the source to avoid saturation in the CCD images. The linear polarization of the Nd:YAG was scrambled with a quarter-wave ($\lambda/4$) plate placed in front of the source.

To compare the backscatter intensities to those at nonzero viewing angles, the source–target–detector angle around the 0° backscatter angle was changed by rotating the beam splitter to change the angle of incidence to the sample and, hence, the viewing geometry.

D. Samples

As the study started with a search of most suitable targets to be used in the ALS campaigns, a large set of different sand and gravel was investigated in the laboratory and during different phases of the study. This is a short description of each sample (the abbreviations used for each sample hereafter have also been included in parentheses).

A set of industrial samples was obtained from Lohja Rudus Ltd. and included sand used in children's playgrounds for sandboxes (Play) and producing safe grounds, e.g., under swings (Safety). The play sand has a structure suitable for dense packing, whereas the safety sand does not compress easily. There are also sand used in construction, such as concrete (Concrete) and fine structured filling (Filler), and golf courses (Golf). The grain size range of these sand samples varied between less than 1 and 8 mm (concrete sand having the largest grain sizes, whereas all others were less than 5 mm).

Another set of samples consisted sand and gravel available in standard hardware stores and commonly used in construction and gardening. The samples included black diabase (Diabase) and yellow quartz (Quartz), crushed light expanded clay aggregate (LECA), which consists of lightweight particles of burnt clay (LECA), and a sample of coarse gravel used for sanding the roads (Gravel). To complement the sample variety, another set was acquired, including black gabbro (Gabbro), crushed redbrick (C Brick), and two samples of sandblasting sand with grain sizes of 0.1–0.6 mm (Sand01) and 0.5–1.2 mm (Sand05). Some miscellaneous targets were also included in the study, such as a piece of polystyrene (Polystyrene) and some natural targets that appeared in the ALS flight campaign sites: beach sand (Beach) and gravel from Espoonlahti boat harbor (Harbor) and a sample of bunker sand (Bunker) from the Lakisto golf course in the Nuuksio target area.

A photograph of all samples is shown in Fig. 3. The size of each container in the image is 11×11 cm.

The ALS calibration was tested for golf greens and bunkers measured at the Nuuksio 2006 Optech and Nuuksio 2007 Leica ALS campaigns. The greens are mostly flat (or slightly sloped), and the grass is uniform and short. The bunker sand is usually carefully raked to produce an even surface. This means that



Fig. 3. Samples. (Top row) Play, Safety, Concrete, Filler, and Golf (Lohja Rudus sand). (Second row) Diabase, Quartz, LECA, and (sanding) Gravel. (Third row) Gabbro, Crushed Brick, Sand 0.1–0.6 mm, and Sand 0.5–1.2 mm (commercial samples). (Lowest) Polystyrene and natural targets: Beach and Harbor sand and gravel, and Bunker sand.

there is little variation from target to target, which makes them ideal targets for testing and evaluating the calibration procedure.

III. RESULTS AND DISCUSSION

A. Relative Reflectance Variations Between Laboratory and Terrestrial Laser Scanner

To investigate the consistency of results between different instruments and the further corrections needed to compare the results, we present the calibrated reflectances of all samples measured at the laboratory with the FARO terrestrial laser scanner and the Nd:YAG 1064-nm laser and CCD camera in Table II. For Nd:YAG/CCD data, each data point is an average of five images of 20-s CCD exposure. All reflectances in Table II are relative to the 99% Spectralon (Labsphere Inc.) reference target measured similarly to the samples. The Spectralon standard is widely used in spectroscopic applications to represent a Lambertian surface.

There is some disagreement between the reflectance values in Table II, which results from several factors that require further correction or must at least be taken into account when comparing results from different instruments. To summarize, the most important factors that may cause variation in the results are the following:

- 1) the aperture size of the light source and detector;
- 2) the wavelength differences;
- 3) measurement geometry: the angle of incidence;
- 4) the wetness of the targets;
- 5) the uncertainty of the backscatter measurement;
- 6) the polarization effects;
- 7) the scale difference between laboratory and airborne measurement;
- 8) the effects of the echo detection algorithm and possible gain control of an laser scanner.

TABLE II
COMPARISON OF RELATIVE REFLECTANCE MEASURED AT THE LABORATORY WITH THE FARO TLS AND THE Nd:YAG LASER AND CCD

Sample	FARO 785 nm	Nd:YAG + CCD 1064 nm
Play	0.26	0.33
Concrete	0.25	0.30
Golf	0.17	0.23
Safety	0.23	0.22
Filler	0.32	0.42
Diabase	0.16	0.36
Quartz	0.41	0.34
Gravel	0.26	0.25
LECA	0.11	0.13
Gabbro	0.09	0.14
C Brick	0.26	0.61
Sand05	0.26	0.23
Sand01	0.26	0.32
Beach	0.18	0.19
Harbor	0.16	0.17
Polystyrene	0.91	0.59
Bunker	0.25	0.24

Reflectances relative to 99% Spectralon®. No aperture or wavelength corrections have been applied (see Sect. IIIA).

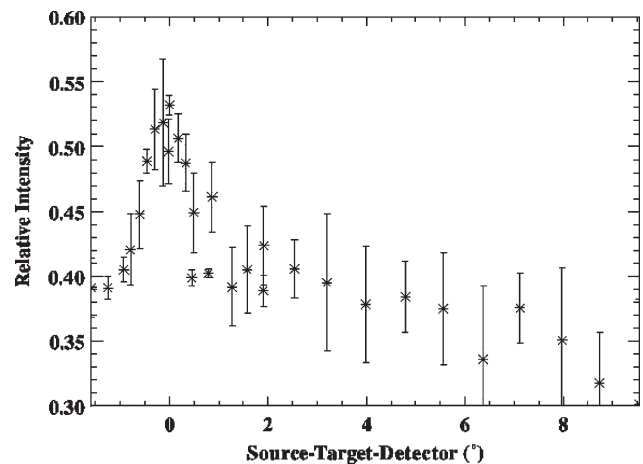


Fig. 4. Intensity versus source–target–detector angle (0° is the exact backscatter direction) for the C Brick sample. The intensity is peaked toward the 0° viewing geometry. The error bars are the standard deviations of each data point (which is an average of five 3-second CCD exposures).

In this study, the correction with respect to the aperture size was carried out for laboratory (Nd:YAG and FARO) data, as well as a wavelength normalization for the FARO results. The rest of the effects were either negligible in these measurements or could not be taken into account because of the lack of information (such as the echo detection). In what follows, we discuss each of these factors and their effects in more detail.

- 1) The aperture widths of the light source and detector typically cause a significant flattening of the measured intensity curve at small source–sample–detector angles (backscatter, see Fig. 4 for an intensity versus angle curve), particularly at angles corresponding to the angular aperture widths θ_i of the source and the detector as seen from the sample, i.e., the sum of

$$\theta_i = 2 \arctan \frac{d/2}{R} \quad (3)$$

where d is the source/target aperture diameter and R is the distance to the target (see [16] and [21] for a more detailed discussion of the aperture effect). The relative decrease D in measured intensity has been shown to be approximately [21]

$$D = \frac{s\alpha}{4\omega} \quad (4)$$

where s is the relative enhancement in the backscatter intensity of the target, α is the combined angular aperture size of the source and detector, and ω is the width of the nonlinear backscatter intensity peak (such as that in Fig. 4). Because of the distances of the airborne instruments, the angular aperture of an airborne laser scanner is almost negligible, and typically produces a drop of the order of 0.5% in the measured intensity [21]. As the terrestrial (TLS) and laboratory instruments have significantly greater angular apertures, we have applied the correction [(4)] into the Nd:YAG and FARO TLS measurements. For this, the intensity enhancement s and its angular width ω for each target have been taken from a large database of backscatter measurements presented in our previous studies ([22] and references therein): s is computed from these measurements to be approximately $(I(0^\circ) - I(5^\circ))/I(0^\circ)$ (where the 5° viewing angle is assumed to be outside the angular range where the target intensity is peaked due to backscatter effects), and since ω is typically within 1° for the sand and gravel type of targets [22], we have approximated $\omega = 1^\circ$ for all targets. The backscatter effects have been measured for all targets except for Diabase, Quartz, and Bunker, for which s was approximated with the aid of similar types of targets (e.g., Gabbro and sand).

- 2) As there is a wavelength difference between FARO (785 nm) and the other (laboratory and airborne) experiments (1064 nm), we normalized the FARO reflectances of the targets used in the Nuukio July 2007 Leica campaign to 1064 nm using their reflectance spectra, measured with a system consisting of flashlight illumination placed right on top of each sample (i.e., the zenith) and the fiber detector of the ASD FieldSpec Pro spectrometer placed at about 30° from the zenith. The reflectances at both wavelengths, calibrated with Spectralon reference plate, are shown in Fig. 5. Slight wavelength differences occur, particularly for the C Brick sample, which has a strong increase in brightness toward the near-infrared wavelengths. Even though the best practice in the future calibration procedures would be to carry out the reference measurements at the same wavelength as the airborne experiments, we used this *ad hoc* correction of FARO wavelengths to be able to compare the airborne laser scanner and TLS (and laboratory laser) results. These comparisons give important information of the target properties and the performance of the instruments at this point of the study. It also turns out that the wavelength differences for this type of targets (namely sand and gravel) are almost negligible for most targets (as it can be seen in Fig. 5).

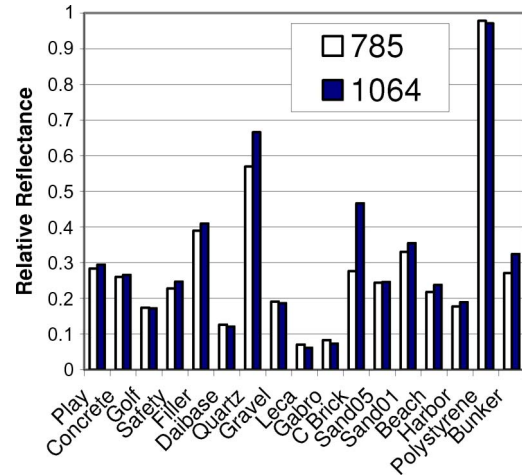


Fig. 5. Wavelength differences between 1064 and 785 nm (from ASD FieldSpec Pro spectroscopy) for all targets. (From left to right) Play, Concrete, Golf, Safety, Filler, Diabase, Quartz, Gravel, LECA, Gabbro, C Brick, Sand05, Sand01, Beach, Harbor, Polystyrene, and Bunker.

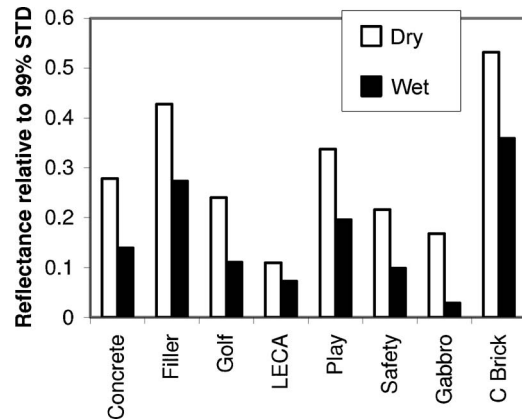


Fig. 6. Effect of target wetness on its reflectance. All wet samples were thoroughly soaked, which produced an evident intensity effect.

- 3) The angle of incidence on the sample has a significant effect on the measurements, particularly at large ($> 20^\circ$) angles of incidence [23] and when range effects are not compensated. As all the laboratory measurements were made at normal (0°) incidence and the incidence angle range for the Leica and Optech measurements were below 5° and 10° , respectively, no corrections were necessary to the results presented in this paper (see [23] for more details).
- 4) The wetness of the target becomes an issue in outdoor experiments. We have investigated the brightness effects for the industrial sand samples obtained from Lohja Rudus and the Gabbro and C Brick samples, and found an evident effect of moisture (Fig. 6), which typically varied from a 30% to 50% drop in reflectance, when the samples were thoroughly soaked. In the experiments and campaigns presented in this paper, the laboratory samples were dry, and as the airborne campaigns were carried out mostly in fair weather conditions, moisture does not play a major role in the present results. However, wetness is an important object of future study, which should include a

measurement of the amount of water in the target and the corresponding effect on its intensity.

- 5) Because of the peaked nature of the intensity in the backscatter measurement geometry (see Fig. 4 for a typical intensity versus measurement geometry), uncertainty and random errors in the measurement are likely. Therefore, strong conclusions should only be made on the basis of a large bulk of results rather than a single observation.
- 6) Polarization effects play a strong role in the backscatter intensity effects (e.g., [24] and [25] and references therein). They are an important object of extensive future studies, which would also provide significant prospects of using the polarization information of the laser scanner intensity data for target classification and characterization (which is being done in, e.g., radar remote sensing of vegetation [26]). In this study, the linear polarization of the Nd:YAG laser was scrambled using a $\lambda/4$ plate in front of the source. The laser sources in airborne and FARO scanners are typically nonpolarized; therefore, the polarization effects were not an issue of this study.
- 7) The scale difference between laboratory and ALS are large, ranging from a few centimeters (laboratory) to some 50-cm footprint (ALS). Even though the laboratory laser footprint size was increased by sample rotation during long (up to 20 s) exposures, more information is needed about the scale variations (with respect to the scale variation in target surface structure), particularly in the airborne laser measurement (see also [23]). The upcoming future flight campaigns will increase the airborne intensity database and provide a larger sampling to investigate these effects, as well as other effects arising from differences in instrumentation and measurement technique.
- 8) One of the factors in an exact range measurement is the echo detection algorithm. Since the length of the laser pulse is longer than the accuracy needed, a specific timing in the return pulse needs to be defined. In a non-waveform ranging system, analog detectors are used to derive discrete time-stamped trigger pulses from the received signal in real time during the acquisition process, whereas a software-based solution can be applied in the postprocessing stage of waveform data using, e.g., leading edge discriminator/threshold, center of gravity, maximum, zero crossing of the second derivative, and constant fraction. Unfortunately, most commercial ALS systems do not provide detailed information on the analog detection method, even though different detection methods may cause some changes into the range and intensity estimates [27], [28]. In practice, strong intensity causes the widening of the echo and, thus, the change of the obtained timing and range measurement. Therefore, some of the ALS systems (e.g., the Leica ALS-50II) use automatic gain control (AGC) to keep the returned power within a certain limit. This helps in keeping the high accuracy in range, but it also distorts the intensity value. By the AGC value, the accurate intensity should be decrypted, preferably with the information given by the system provider. In this paper, there were differences

TABLE III
REFLECTANCES FROM ESPOONLAHTI DECEMBER 2006 FLIGHT CAMPAIGN, COMPARED WITH APERTURE CORRECTED REFLECTANCES FROM LABORATORY (FARO TLS AND Nd:YAG) MEASUREMENTS. ALL MEASUREMENTS ARE RELATIVE TO THE (SANDING) GRAVEL

Sample	Espoo Dec 06 TopEye	FARO	Nd:YAG (0°)
LECA	0.40	0.42	0.52
Gravel	1.0	1.0	1.0
Diabase	0.67	0.59	1.45
Quartz	1.15	1.59	1.36

N.B. The wavelength difference between FARO and other instruments has not been corrected in this table, which may have caused differences between FARO and other measurements.

in the AGC values between the scanner sweep directions, which resulted in differences up to 10% in the intensity values in the Leica ALS data. The AGC was not used in the Optech ALTM scanner.

B. Choice of Gravel Practical for Calibration

Comparison of the measurements made with terrestrial instruments (i.e., the TLS and the laboratory laser instrument) and the results from the first airborne test campaign in Espoonlahti (December 2006) gave us some valuable practical information about the properties that are crucial for the calibration samples to be reliable. The targets for the Nuuksio July 2007 flight campaign were chosen according to the experience from these experiments. Here, we discuss the most important criteria.

Consistency between laboratory and laser scanner measurement, i.e., the deviation in data from different experiments should be as small as possible, even though systematic and random errors would always cause inaccuracy and the calibration would therefore be best to perform with the same instrument as the measurements. However, consistency between different instruments seems to be a good measure of the stability of the target and the performance of the instruments; therefore, the laboratory reflectance calibration is essential for the selection and use of the gravel samples, and it is important that the results are consistent even in the laboratory scale. The footprint of an airborne laser scanner might allow larger scale variations in the target structure and surface brightness, but reproducing such results with a collimated laser source [which is needed to reproduce the backscatter measurement geometry of laser scanners (e.g., [7] and [19])] proves a challenge if the targets are not uniformly structured. Preliminary tests have shown that grains with matte surfaces and uniform color range (and surface structure) with respect to the dimensions of the measurement (laser spot/footprint size) produce most stable results, whereas, e.g., glossy and crystallike grains cause specular reflections, which may lead to different results at different measurement scales and cause strong deviation in data (cf. [23]). This can be seen in Tables III and IV, where the results for, e.g., Diabase and Quartz (Table III) show large differences, whereas the reflectance levels for, e.g., LECA (Tables III and IV) and Sand01 (see Fig. 7) are better reproduced. The differences are also seen in the aperture corrected reflectance plot (Fig. 7).

Easy (commercial) availability of the targets in standard hardware stores was one of the starting points of this study.

TABLE IV
REFLECTANCES FROM NUUKSIO JULY 2007 FLIGHT CAMPAIGN,
COMPARED WITH APERTURE CORRECTED REFLECTANCES FROM
LABORATORY (FARO TLS AND Nd:YAG) MEASUREMENTS.
ALL MEASUREMENTS ARE RELATIVE TO THE SAND01 SAMPLE

Sample	Nuukisio Jul 07, Leica	FARO	Nd:YAG (0°)
LECA	0.36	0.47	0.40
Gabbro	0.30	0.38	0.45
C Brick	2.16	1.12	1.91
Sand05	0.75	1.02	0.70
Sand01	1.0	1.0	1.0
Bunker	0.93	0.99	0.74

N.B. The wavelength difference between FARO and other instruments has not been corrected in this table, which causes differences between FARO and other measurements.

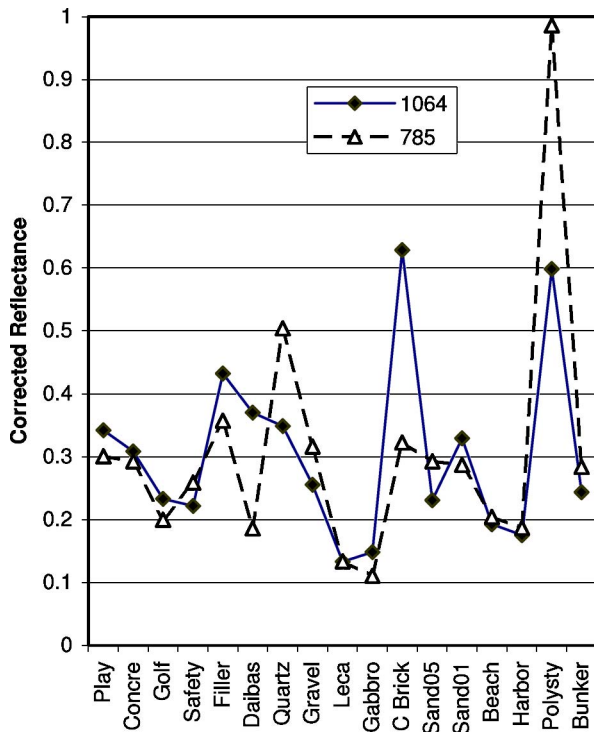


Fig. 7. Laboratory measurements of all samples [(from left to right) Play, Concrete, Golf, Safety, Filler, Diabase, Quartz, Gravel, LECA, Gabbro, C Brick, Sand05, Sand01, Beach, Harbor, Polystyrene, and Bunker] with the 1064-nm Nd:YAG and FARO (785 nm). The reflectances are corrected with respect to the aperture size difference.

This would be practical for the calibration of airborne laser data taken at different campaigns in varying locations. The sand and gravel tested in this study are commonly used in sandblasting (Sand01 and Sand05), construction (e.g., LECA, Play, and Safety sand) and gardening (e.g., C brick, Quartz, Diabase, and Gabbro). They are available in small quantities in hardware stores or in bulk from the manufacturer. This also provides an easy replacement when dirt accumulates and causes a change in the target optical properties, and when there are damages that might occur because of weather effects (e.g., in case of flight delays) or during transportation, setup, or between consecutive flights.

It was also important that the targets were *easy to transport*. This is why we also included some lightweight targets into the study (LECA and Polystyrene) and made some preliminary tests with some natural sand targets that were available on

site without transportation (Beach, Harbor, and Bunker sand). In particular, if a grayscale is needed, a large set of gravel has to be transported, and the total weight easily sums up to several thousands of kilograms. However, it turns out that, at this point, the stability of the target between measurements is a more important criterion than transportability. For example, the Harbor and Bunker targets showed a great variation and were not ideal choices for calibration purposes.

Distinctly different reflectances within a set of targets would provide the best grayscale, particularly if the performance of the instrument (particularly the linearity of the detector) at different brightness scales must be evaluated. The preliminary test measurements for a large set of gravel showed that it is difficult to find a gravel target of high reflectance suitable for calibration. Therefore, to extend the brightness scale toward higher reflectances, we included a sample of Quartz and Polystyrene into the investigation but these targets were not the most stable ones either.

We also wanted to investigate the *role of surface roughness* by the choice of samples with different roughness scales (from 0.1 mm to the centimeter scale). The first results suggest that the color and brightness variations within the target would play a stronger role than the differences in grain size, but more results, particularly from ALS, would be crucial for further investigation on the effect of surface properties.

Little variation with the measurement geometry: A strong enhancement in intensity toward backscatter has been detected for all the samples and is evident because of the ubiquitous nature of the effect [20] (see Fig. 4 for a typical intensity versus backscatter angle function). Therefore, the backscatter intensity enhancement cannot be a criterion for selecting the targets, but should be taken into account when comparing the laser scanner-based intensities to those obtained with passive instruments (e.g., aerial images), which mostly operate at different measurement geometry than backscatter. The incidence angle dependence was relatively low for the chosen samples in the angular range of the airborne campaigns (see Section III-A and [23]).

The first set of gravel was measured in the Espoonlahti December 2006 flight campaign (TopEye MKII, see Table I for details). The results plotted in Table III show that all gravel in the set (except for LECA) showed poor repeatability between measurements. This is most likely due to the inaccuracy in laboratory (laser and FARO) experiments caused by, e.g., strong specular reflections, particularly for Quartz and Diabase, as discussed previously.

An improved (with respect to the aforementioned criteria) set of gravel was chosen for the Nuukisio July 2007 campaign (Leica ALS50). The results in Table IV show somewhat better agreement, particularly between the 1064-nm Nd:YAG and Leica ALS results, and enabled a further test and analysis of the calibration properties.

C. Nuukisio July 2007 Airborne Campaign

Fig. 8 shows the gravel setups at both Nuukisio 2007 and Espoonlahti 2006 campaigns. Fig. 9 shows the intensity plot (raw data) of the entire set of gravel set up at the Lakisto golf course during the Nuukisio 2007 flight campaign. The



Fig. 8. (Left) Calibration gravel samples set up for the Nuuksio July 2007 ALS campaign. (Clockwise from top left) Crushed redbrick (C Brick), sandblasting sand (Sand01), black gabbro (Gabbro), crushed LECA (LECA), and sandblasting sand (Sand05). (Right) The gravel samples at the Espoonlahti December 2007 campaign. (From top downward) Gravel, Quartz, Diabase, and LECA.

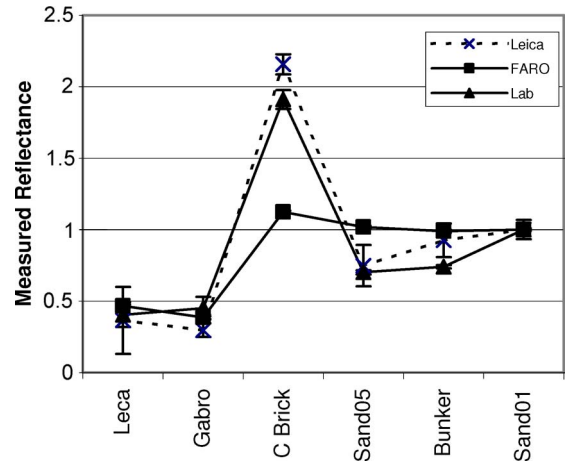


Fig. 10. Target reflectances at the Nuuksio July 2007 ALS flight campaign compared with laboratory (Nd:YAG, denoted in the legend as “lab”) and FARO TLS) data (uncorrected with respect to the aperture and wavelength differences). The error bars represent the standard deviations of the averaged data points for each target. The reflectances are presented relative to Sand01.

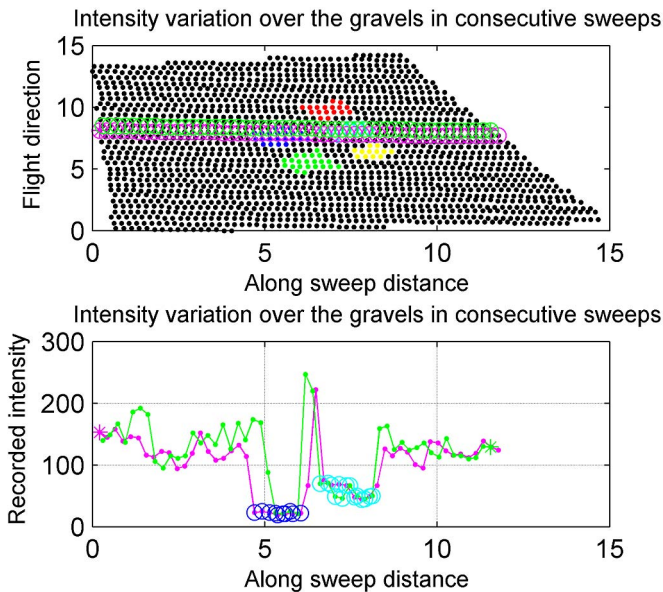


Fig. 9. (Top) Laser range data points of the Nuuksio July 2007 gravel targets. (Below) Intensity raw data (pulse amplitudes of two consecutive scanner sweeps) of the cross section marked with horizontal lines in the top panel. The intensity of (left) Gabbro and (right) Sand05 is marked with blue and turquoise, similarly to the range points in the upper panel.

raw data intensity levels imply that the targets had produced distinguishable intensities. The intensity points corresponding to each target were averaged and scaled at a 500-m altitude. The scaling was done by means of multiplying the original intensity by the ratio of the squared distance and the squared reference distance (500 m). The result was then divided by the squared atmospheric transmittance calculated with the MODTRAN software (using the midlatitude summer model parameters with rural aerosols and 23-km visibility, see [18] for details).

The calibrated reflectances are shown in Fig. 10. The calibration included the correction of returned intensity as a function of range and atmospheric attenuation described previously [18]. Comparison with laboratory (Nd:YAG and FARO) data (uncorrected with respect to the aperture and wavelength dif-

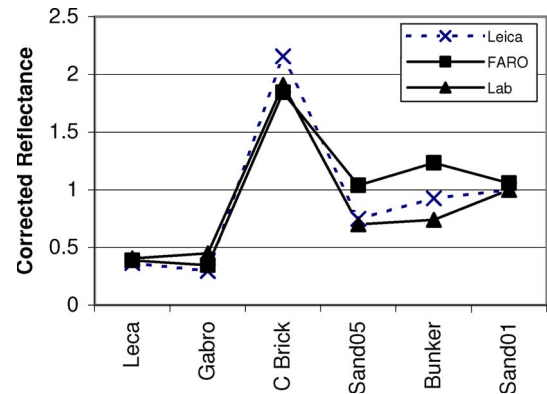


Fig. 11. Nuuksio July 2007 target reflectances, compared with laboratory (Nd:YAG and FARO TLS) measurements. The laboratory measurements are corrected with respect to the aperture angle, and the FARO measurements have been corrected for wavelength differences. The reflectance values are presented relative to the Sand01 sample.

ferences) is also presented. The error bars shown in Fig. 10 are the standard deviations of the relative reflectances. The standard deviations for these targets in the Leica, Faro, and Nd:YAG measurements are on the order of 0.05–0.2, 0.01, and 0.01–0.09, respectively. In Fig. 11, the Nd:YAG and FARO reflectance values were corrected with respect to aperture size [(3) and (4)] and the FARO reflectances were normalized to a 1064-nm wavelength (cf. Fig. 5 where the wavelength differences are plotted for all samples). It must be noted from Figs. 10 and 11, however, that the aperture size effect does not seem to be the greatest error source in these results.

The agreement in the results is mostly better between the airborne laser scanner (Leica) and laboratory (Nd:YAG/CCD) measurement than that with the FARO terrestrial scanner. In spite of the random errors and inaccuracy because of the measurement geometry, it can be observed that the agreement with those samples with most uniform surface color, i.e., LECA, Gabbro, C Brick, and Sand01, is better. Sand01, the sandblasting sand with the finest grain size, is normalized to 1.0 in Figs. 10 and 11, but the original reflectance values are

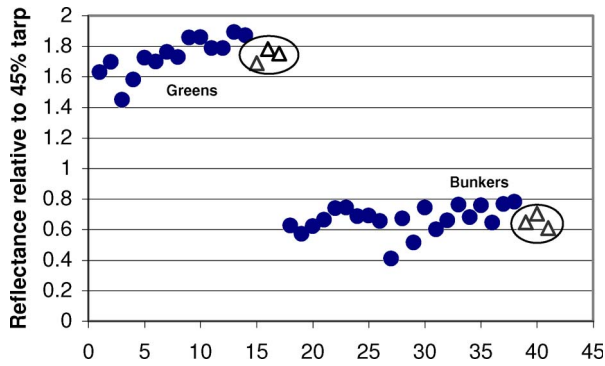


Fig. 12. Relative reflectances of greens and sand bunkers in (circles) Master Golf and (triangles) Lakisto. The approximate reflectance levels between different campaigns coincide. All values are relative to the 45% tarp.

shown in the aperture corrected plot of Nd:YAG and FARO measurements in Fig. 7, showing a reasonable agreement. For this reason and the fact that Sand01 represented the brighter end of the reflectance scale of this set of gravel, it was chosen as the reference for the calibration of the green and bunker intensities.

It must be noted that, in spite of all the corrections, differences in the reflectance values between different instruments still exist. More experiments are needed to find the error sources and possible correction of the remaining uncertainties, and to find out the range where the measurements between different instruments are repeatable. Because relative calibration is mostly carried out with calibration targets measured with the same instrument (and during the same experiment), these uncertainties may not prevent the calibration, even though agreement between different instruments also means a better stability within results from the same instrument (cf. the discussion on target stability in Section III-B) and is therefore necessary in the search and further development of reliable and stable calibration targets. The stability of the calibration target is important to reduce the systematic error in calibrated reflectances caused by possible inaccuracies in the reference target reflectance.

D. Application: Calibration of Grass and Bunker Sand

The airborne test results of the calibration of golf greens and bunkers, measured at the Nuksio May 2006 Optech and Nuksio July 2007 Leica ALS campaigns, are shown in Fig. 12. The data from the May 2006 campaign were corrected for distance and atmospheric transmittance similarly to those in the July 2007 campaign (see Section III-C). Since the aim of the May 2006 campaign was originally to test the use of portable tarps [19], no gravel was available, but the results are calibrated with the test tarp of 45% nominal reflectance. To put the July 2007 results into the same scale, we normalized the reflectance of Sand01 with the 45% target (as Nd:YAG reflectance data exist for both of these, this normalization was possible).

The average reflectance of the greens and bunkers measured in May 2006 (Master Golf) were 1.74 and 0.67, respectively. The corresponding reflectances for July 2007 (Lakisto) greens and bunkers were 1.75 and 0.65, respectively, which indicates a reasonable agreement for a similar type of targets even though there is deviation in data.

Although the number of samples is somewhat low for standard statistical tests, we can apply Student's t-test and the F-test (e.g., [29]) to estimate with what probability the two sample sets (Lakisto and Master Golf) are drawn from distributions that have the same mean. The variances of the sets are essentially the same, and we find that the green samples have the same mean with about 90% probability, while for the bunker samples this probability is about 80%. Thus, we can estimate that the Lakisto and Master Golf samples have similar properties with a statistically significant probability.

These results also point out the feasibility of indirect laboratory calibration in cases where different calibration targets have been used at different campaigns. This means that radiometric calibration of ALS intensity is equally possible with gravel targets as with custom made tarps used thus far.

Further test flights are needed to assess and improve the accuracy of these methods, but since the intensity calibration most often has to be carried out using a limited set of data from a single flight at minimum, it seems clear that a careful planning of the setup of reference targets and the choice of flight lines is required to obtain as many data points as possible, to improve the accuracy of the measurement. A more detailed evaluation of the number of points related to the accuracy of the calibration is also an important object of future study and becomes possible as more data from the future flight campaigns become available.

IV. CONCLUSION

A. Calibration Concept

We have presented a method for airborne laser scanner intensity measurement and calibration using commercially available or *in situ* reference targets. Mass-produced or naturally available sand and gravel can be used in laser scanner intensity calibration, but control over the target properties is essential (particularly in case of natural targets) for the laboratory validation to be feasible and meaningful. Detailed information on, e.g., target and footprint size and point density are also important.

A large bulk of results (particularly from airborne campaigns) will help further to develop this method and validate the presented calibration targets (particularly if a grayscale is desired). A systematic (laboratory) study on wetness effects will also help the situations where the targets have been exposed to weather effects. There is also a need for a more detailed investigation of laser power level variations because of, e.g., the AGC and other technical issues. The radiometric calibration of distributed targets such as forests requires a more detailed study.

B. Application

To our knowledge, this is the first practical demonstration of using reference targets in the calibration of laser scanning intensity data from land targets. The results from the green and bunker experiments show that the relative calibration method is possible in the comparison of reflectance values measured during different campaigns. This study has shown that, even when different calibration targets have been used at separate

flight campaigns, this method is capable of producing meaningful results, i.e., the concept of indirect calibration is feasible for ALS intensity calibration. All these require a systematic laboratory calibration of the reference targets.

As the ALS data interpretation algorithms based on calibrated reflectance combined with point cloud data will be developed, the combined information obtained from laser scanning will provide an effective change detection tool, which has not been available thus far. A wide field of environmental monitoring applications (e.g., in glaciology, agriculture, and forestry) will benefit from the one-shot brightness and topographic information provided by this method.

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