Agricultural and Forest Meteorology 198–199 (2014) 7–14

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Developing a dual-wavelength full-waveform terrestrial laser scanner to characterize forest canopy structure

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ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form 27 June 2014
Accepted 17 July 2014

Keywords:
Terrestrial laser scanner
SALCA
Forest canopy structure
Full-waveform
Dual-wavelength

ABSTRACT

The development of a dual-wavelength full-waveform terrestrial laser scanner to measure the three-dimensional structure of forest canopies is described, and field measurements used to evaluate and test the instrument measurement characteristics. The Salford Advanced Laser Canopy Analyser (SALCA) measures the full-waveform of backscattered radiation at two laser wavelengths, one in the near-infrared (1063 nm) and one in the shortwave infrared (1545 nm). The instrument is field-portable and measures up to nine million waveforms, at the two wavelengths, across a complete hemisphere above the instrument. SALCA was purpose-built to measure structural characteristics of forest canopies and this paper reports the first results of field-based data collection using the instrument. Characteristics of the waveforms, and waveform data processing are outlined, applications of dual wavelength measurements are evaluated, and field deployment of the instrument at a forest test site described. Preliminary instrument calibration results are presented and challenges in extracting useful information on forest structure are highlighted. Full-waveform multiple-wavelength terrestrial laser scanners are likely to provide more detailed and more accurate forest structural measurement in the future. This research demonstrates how SALCA provides a key step to develop, test and apply this new technology in a range of forest-related problems.

1. Introduction

Vegetation canopy structure describes the size, shape, orientation and location, in three-dimensional (3D) space, of canopy components including stems, branches, shoots, and leaves or needles. Canopy structure controls key ecological processes such as light interception and gas exchange between vegetation and the atmosphere, and it determines vegetation productivity and habitat structure at a range of spatial scales; it varies in 3D space in terms of the vertical and horizontal arrangement of canopy elements, and varies in time through plant growth and development (Bonan, 1993; Sellers et al., 1997; Yang and Friedl, 2003). Variations in canopy structure also complicate the interpretation of vegetation reflectance measurements in remote sensing studies and 3D structural forest structural information is required here to improve model-based information extraction from such data (Knyazikhin et al., 2013). Field-based measurements of vegetation canopy structure attempt to capture data on leaf area index (LAI), canopy cover, canopy clumping and vertical foliage distribution, that may be used to drive or test ecological or hydrometeorological models, to calibrate or validate remotely sensed estimates of canopy structural variables, or provide information for management and conservation (Asner et al., 2003; Baldocchi and Wilson, 2001). However, direct measurement of variables like LAI is time-consuming and error-prone in all but the simplest vegetation canopies, and a range of indirect measurement methods have been developed and tested, based on instruments that measure the transmission of radiation through the canopy (Breda, 2003; Jonckheere et al., 2004). These instruments provide indirect estimates of canopy structural variables but require assumptions to be made about leaf angle distribution, foliage clumping and the area of woody stems and branches in the canopy, and they do not provide any information about the 3D arrangement of canopy elements.

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http://dx.doi.org/10.1016/j.agrformet.2014.07.007
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Hemispherical photography (HP) has been used by forest ecologists for the last 50 years (Anderson, 1964a, 1964b; Evans and Coombe, 1959; Rich, 1990) and until the recent development and application of terrestrial laser scanners (TLS), was the only practical means of capturing a permanent record of vegetation canopy structure. HP is normally used to extract information on canopy directional gap fraction that can be used to derive LAI and other canopy variables (Weiss et al., 2004). The main advantages of HP are that it is rapid, cheap and easily deployed in a forest environment, and many studies have attempted to use this approach to estimate LAI in forest and woodland canopies (e.g., Chen et al., 1997). The main weaknesses of HP are that, the analysis normally requires a manual interpretation stage to set a threshold between sky and vegetation pixels, the measurements are affected by variation in camera exposure and sky conditions at the time of measurement, and it is generally very difficult to separate woody elements from foliage elements because the photographs are effectively analysed as binary images (Leblanc et al., 2005). Furthermore, HP provides only a two-dimensional representation of canopy structure projected onto a plane, so that important canopy characteristics like height, leaf and crown shape, and gap size, cannot readily be determined.

The recent development of TLS technologies has provided an opportunity to rapidly capture detailed information on the 3D characteristics of vegetation canopies. TLS combine a laser range-finding measurement and recording system with a two-axis scanning mechanism, and automatically capture 3D point clouds, consisting of many millions of samples, that may be reconstructed to represent the 3D structure of the object scanned. Commercially available TLS provide very precise range measurements over long distances, and are designed to provide 3D models of buildings, terrain, rock outcrops and industrial infrastructure. However, they are generally not suitable for measuring forest canopies because their scanning geometry is often sub-optimal, they record at just one laser wavelength and, with a few exceptions, they record only discrete returns, rather than the full-waveform of backscattered laser energy. In addition, the measurement characteristics and data processing algorithms used by commercial TLS manufacturers are often proprietary, and are not made available to the end-user, making it difficult to work with the radiometric information provided by TLS.

This paper describes the first operational dual-wavelength, full-waveform terrestrial laser scanner, designed specifically for measuring the 3D structure of forest canopies. The Salford Advanced Laser Canopy Analyser (SALCA) is a research instrument that allows a wide range of experiments to be undertaken to examine the interaction of laser radiation with forest canopies, to develop a better understanding of the measurement characteristics of TLS, and to test a range of new methods to characterize forest structure. The objective of this paper is to describe and justify the design of the instrument, to illustrate its measurement characteristics, and outline a range of potential applications using field data sets collected as part of the programme of instrument development.

2. Terrestrial laser scanning of vegetation canopy structure

Most TLS operate using a short pulsed time-of-flight measurement to determine the range of objects within the laser beam and digitize the time-dependent backscattered energy for each pulse. A number of recent studies have demonstrated the potential of TLS for characterizing vertical forest canopy foliage profile, directional gap fraction, chlorophyll content, and LAI (e.g. Beland et al., 2011; Danson et al., 2007; Eitel et al., 2010; Garcia et al., 2011; Lovell et al., 2003; Moorthy et al., 2008; Radtke and Bolstad, 2001; Tanaka et al., 1998, 2004). However, commercially sensitive, and unknown, echo detection algorithms are usually applied to these data to detect ranges to a limited number of targets. These may include returns triggered by objects only partially occupying the laser beam, resulting in errors in estimating gap fraction. This effect may lead to an under-estimation of gap fraction and over-estimation of LAI (Beland et al., 2014; Ramirez et al., 2013). Without knowledge of the echo detection algorithm applied, correcting for such effects is difficult.

Full-waveform TLS can record the range to multiple targets and allow the application of alternative echo detection algorithms, and varying sensitivity thresholds, for detection of multiple objects intercepting the laser beam, and provide the potential for full quantitative interpretation of the radiometric intensity of the backscattered signal. However, only a few full-waveform terrestrial laser scanners have been developed and used for field measurements of forest structure. The RIEGL VZ-400 (RIEGL Laser Measurement Systems GmbH, Horn, Austria, www.riegl.com), performs ‘online waveform analysis’ to provide range, intensity, pulse width, and quality information, but does not allow end-user access to the full waveform since the background noise used in the echo detection algorithm is not recorded. In spite of this limitation, recent applications of this instrument have illustrated its potential for forest structural measurements (Beland et al., 2014; Vaccari et al., 2013). The CSIRO Echidna® (Strahler et al., 2008; Yang et al., 2013; Yao et al., 2011; Zhao et al., 2011, 2012) was a prototype single-wavelength system, recording full-waveform data, that laid the foundations for the development of this new technology, but it is no longer operational and was never commercially available. Both the RIEGL VZ-400 and Echidna® use a single laser wavelength at around 1550 nm which can limit their application when trying to separate canopy components (e.g. branches and leaves) based on differences in return intensity, as intensity is influenced by both reflectance properties of the components, the amount of material in the beam, as well as the local incidence angle. Such influences cannot be separated in a single wavelength measurement. One way to try to overcome this limitation, and better distinguish canopy components, is to take measurements at multiple wavelengths and make use of spectral ratios (Hancock et al., 2012).

A number of prototype, mainly laboratory-based, multispectral laser scanner systems are under development for use in vegetation applications. Rall and Knox (2004) developed the dual-wavelength Spectral Ratio Biospheric Lidar, to examine changes in return intensity from a tree canopy resulting from phenological variation. Woodhouse et al. (2011) recently developed the Multispectral Canopy LiDAR system that uses a single tunable laser aimed at measuring NDVI and Photochemical Reflectance Index and designed to be a prototype airborne sensor (Morsdorf et al., 2009; Wallace et al., 2012). Chen et al. (2010) used a supercontinuum laser source to measure waveforms reflected from tree samples at two wavelengths in a bench-top experiment. Wei et al. (2012) developed a four-channel instrument and demonstrated its application to measure surface reflectance and Gong et al. (2012) tested a laboratory-based multi-wavelength LiDAR for vegetation remote sensing. A prototype multispectral full-waveform LiDAR instrument has also been successfully developed and tested for vegetation measurements in a laboratory setting as described by Hakala et al. (2012) and Vauhkonen et al. (2013).

These multi-wavelength instruments are all still under development and not yet ready for routine deployment in forest environments; however two dual-wavelength full-waveform instruments have already been deployed in field-based experiments. The first is the Dual Wavelength Echidna LiDAR (DWEL) developed by the University of Boston, University of Massachusetts, Boston, University of Massachusetts, Lowell, USA, and CSIRO, Australia (Douglas et al., 2012). The second is the Salford Advanced Laser Canopy Analyser (SALCA) developed by the University of

Salford, UK, and described in this paper. These two instruments have been developed independently and, although they both measure two laser wavelengths (approximately 1064 and 1550 nm), other measurement characteristics of the systems, like beam size, beam divergence, and pulse length, are markedly different. Work is currently underway to compare the data from these two instruments as part of an international terrestrial laser scanner inter-comparison study (Armston et al., 2013) and no further details of the DWEL instrument are provided here.

3. SALCA: instrument concept and design

The Salford Advanced Laser Canopy Analyser (SALCA) was developed by the University of Salford and Halo Photonics Ltd., as the first dual-wavelength full-waveform terrestrial laser scanner designed for field-based characterization of forest and woodland canopy structure. The instrument records the full waveform of backscattered energy with a range resolution of 15 cm and a maximum range of 105 m in two asynchronously emitted wavelengths in the near- and middle-infrared (1063 and 1545 nm). SALCA is rugged, weather-proof and field-portable (weight 15 kg) and designed to be deployed on a surveying tripod on the forest floor. It requires a 24 V power supply (a 24 V 20 Ah $LiFePO_4$ battery provides 5 h of scan time) and the control software is operated using remote desktop software and a wired or wireless connection. The scan data are stored on-board and downloaded at the end of the data collection period.

SALCA is designed to acquire laser measurements over a complete hemisphere above the instrument. The scanner body moves slowly in azimuth over 0–180° in selectable angular resolution steps of 1.05, 2.1, or 4.2 mrad, and a rotating scanner head, equipped with a 45° mirror, rotates rapidly (1 Hz) deflecting the beam 360° in zenith (Fig. 1). Combining the pulse repetition rate of 5 kHz, and the speed of rotation of the scanner head, the highest resolution setting results in 3200 laser shots per revolution of the scan head over a zenith angle range of +96° to −96°, and 3000 steps of the scan head to cover the azimuth range 0–180°. The scan pattern is radial with every azimuth scan line intersecting at 0° zenith so that the density of sampling is high at high zenith angles (generally the forest canopy) and lower at low zenith angles.

The two lasers follow the same optical path and are well aligned but, since only one detector is used, they fire asynchronously, resulting in a small offset in the footprints, in the zenith direction only, equivalent to less than 1% of footprint area. The backscattered energy from each pulse is detected and then digitized at 1 GHz using 8-bits, resulting in a two-wavelength full-waveform data record that measures the intensity of backscattered energy from objects in the beam up to 105 m from the instrument. The Gaussian beam diameters, defined as the width between the points where the intensities are approximately 13.5% of the maximum intensity (I_{max}), or I_{max}/e^2, as they leave the instrument are very small (Table 1). With a beam divergence of 0.56 mrad, the footprints have diameters of 8.0 mm (1063 nm) and 9.2 mm (1545 nm) at a range of 10 m.

When scanning at full resolution (1.05 × 1.05 mrad) SALCA records 9.6 million dual-wavelength waveforms in approximately 110 min; most of the results shown in this paper are derived from low resolution (1.05 × 4.2 mrad) scans that are recorded in approximately 25 min. In addition to providing hemispherical scans, SALCA can operate in a 'stare mode', recording repeated pulses at a specified fixed azimuth and zenith angle, which is useful for assessing beam alignment and scan geometry, and conducting experiments where it is necessary to create interactions with a specific targets. Key system characteristics for the instrument are presented in Table 1.

Table 1
SALCA system specifications.

Wavelength	1063 nm and 1545 nm
Pulse length	1 ns
Pulse rate	5 kHz
Beam width at sensor	2.4 mm for 1063 nm and 3.6 mm for 1545 nm
Beam divergence	0.56 mrad
Detector field of view	5 mrad
Sampling rate	1 GHz
Range resolution	15 cm
Maximum range	105 m
Angular sampling step in azimuth	1.05 mrad
Angular sampling in zenith (selectable)	1.05/2.1/4.2 mrad
Angular displacement between wavelengths	6 μrad

4. Instrument tests and potential applications

SALCA is an operational instrument that has been deployed in laboratory and field experiments since 2011 (Danson et al., 2012). Work has been undertaken in a laboratory setting to characterize the radiometric and geometric properties of the measurements, and to investigate the application of the instrument to measure leaf water content. It is also currently being deployed in a range of field campaigns to test, amongst other things, the application of SALCA data for monitoring forest canopy growth dynamics, for LAI and cover estimation, and to assess forest canopy water status. The following section aims to illustrate the key characteristics of the data recorded by the instrument and uses field data collected at Delamere Forest, Cheshire, UK, between 2011 and 2014. Delamere Forest is a mixed-species woodland of around 970 ha owned and managed by the UK Forestry Commission; its consists of stands of managed conifers, mainly Scots pine (*Pinus sylvestris*) and Corsican pine (*Pinus nigra* var. *maritima*), and areas of mixed deciduous species, including oak (*Quercus robur*), birch (*Betula pendula*), common beech (*Fagus sylvatica*) and sweet chestnut (*Castanea sativa*). The field measurements to date have used fixed survey plots in both evergreen and deciduous stands described in detail in Ramirez et al. (2013).

4.1. Full waveform data recording and analysis

SALCA digitizes the intensity of the backscattered energy at a rate of 1 GHz resulting in a sample every 15 cm in range, up to the maximum range of the sensor (105 m). For every laser pulse the recorded waveform therefore consists of 700 8-bit samples for the 1545 nm wavelength followed by 700 samples for the 1063 nm wavelength. Target detection involves the application of an adjustable noise threshold and the identification of data points above this threshold. This approach requires that the instrument noise is both stable and predictable and in the case of SALCA it has been found to be very stable with the DN varying over a range of only 3–4 DN. Furthermore, since only one detector is used, the noise characteristics are identical for both wavelengths so that a single noise threshold may be applied to the data in both wavelengths (see Fig. 2). Examples of SALCA system waveforms are shown in Fig. 2, extracted from a full hemisphere low resolution (1.05 × 4.2 mrad) scan at a mixed oak/birch stand at Delamere Forest in July 2011. At zero range there is a signal from the internal reflection within the instrument optics of the outgoing laser pulse in both wavelengths and this is normally used to set the zero range for each waveform separately. The single return is from a tree stem at a range of 12.8 m and is the only object detected in that particular laser shot. There is a strong return (high intensity) from the object in both wavelengths indicating that it occupies a large proportion of the beam and has

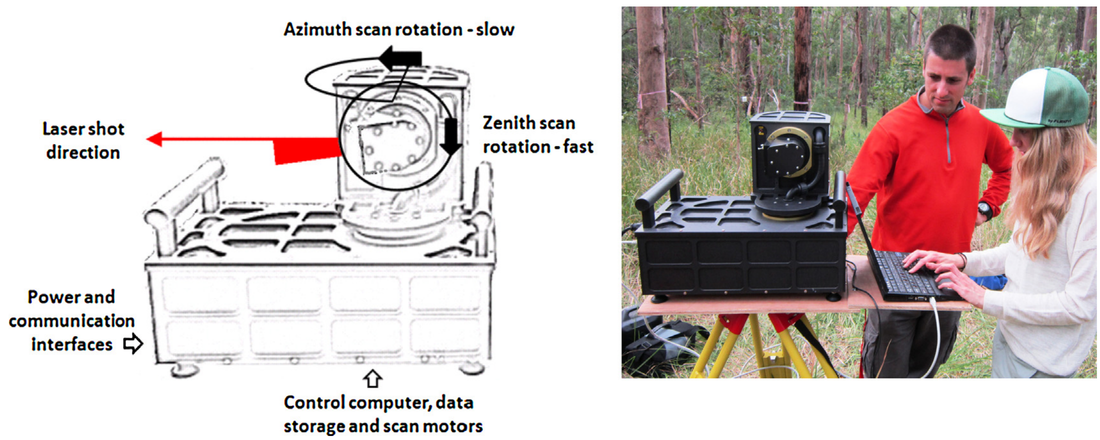

Fig. 1. Sketch of SALCA showing two-axis rotation and laser shot direction (left) and deployed in the field (right) (reproduce in colour on web only.)

a relatively high reflectance at both wavelengths. The two-return waveform is from the canopy and records objects at range of 14.30 and 15.00 m; the higher DN of the second return indicates that the object is larger and/or more reflective at both wavelengths than the object triggering the first return.

Further quantitative application of these data requires calibration to ‘apparent reflectance’ taking into account the range dependence of laser intensity and the response of the detector to input energy (Kaasalainen et al., 2009). Calibration can be achieved using targets with known reflectance positioned within scans (Gaulton et al., 2013a) and a comprehensive calibration procedure is now being developed for SALCA using data collected in an international laser scanner inter-comparison study in 2013 (Armston et al., 2013), with initial results illustrated later in this paper.

Fig. 3 shows an example of a dual-wavelength multiple return point cloud from a hemispherical scan for the same oak/birch plot, with the return number coloured according to range. The first returns are from all parts of scene including understory vegetation, main stems, and the canopy overhead. The second returns are from the canopy or partially occluded areas of stem and understory, and the main stems show no returns as expected (single return). Third returns are recorded at close range from the understory, or at 15 m or more in the canopy. There were a small numbers of fourth, fifth and sixth returns, mainly from the canopy. Up to eight returns have been detected in the scans recorded at various forest plots from the Delamere Forest site. Higher frequencies of second and third returns for the 1545 nm wavelength may be related to the higher power output of this laser module.

To date, two echo-detection algorithms have been applied to the data to detect the range and magnitude of all returns. The first uses the maximum return value for a given target as the recorded intensity; this has been shown to be relatively noisy when observing extended targets with uniform reflectance characteristics. The second uses the sum of all intensity values above noise threshold for a given object providing data with a larger dynamic range and less noise. Other echo detection algorithms, including the use of Gaussian and quadratic fitting, are currently being tested, and compared with the current methods. This work indicates that the short pulse length of SALCA (1 ns or about 30 cm) means that it is possible to identify discrete objects within this range, but that the number of measurements available for fitting smooth functions to the returns makes range determination with SALCA less accurate than systems with longer pulses or shorter range bins.

4.2. Dual wavelength applications

The dual-wavelength measurement characteristics of the SALCA provide an opportunity to explore the 3D spectral properties of forests with a terrestrial laser scanner. A key design characteristic is that the dual wavelength measurements may be used to derive a ratio of ‘apparent reflectance’ that is insensitive to the amount of material intercepting the beam and the laser incidence angle, thereby allowing classification of the point cloud into different spectral components. If the ratios differ between woody and leaf material in a consistent way, then a simple threshold will allow separation of laser returns from these two canopy components. This may then provide a way to measure true LAI (assuming knowledge of clumping), rather than the plant area index (PAI) generally measured by HP or other indirect imaging instruments. This approach will depend on accurate calibration of the data to apparent reflectance and spectrally distinct woody and leafy material in the canopy.

As an initial test of this approach, a full hemisphere dual-wavelength scan from a mixed broadleaved (oak and birch) stand

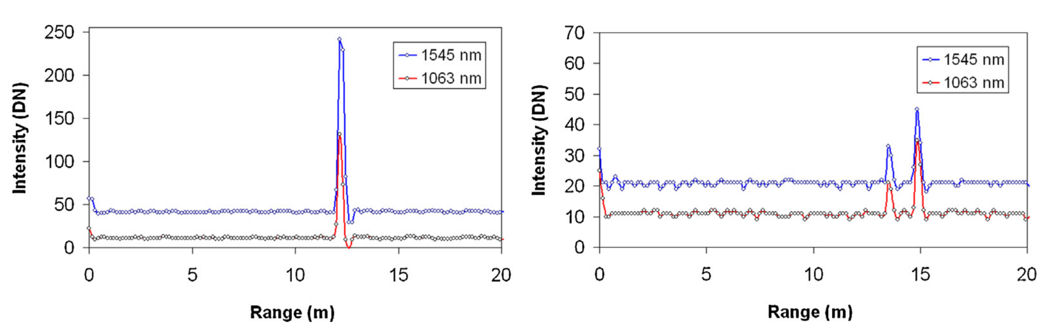

Fig. 2. Examples of SALCA dual-wavelength waveforms with one return (left) and two returns (right). The 1545 nm waveforms have a positive offset in both cases for clarity (reproduce in colour on web only.)

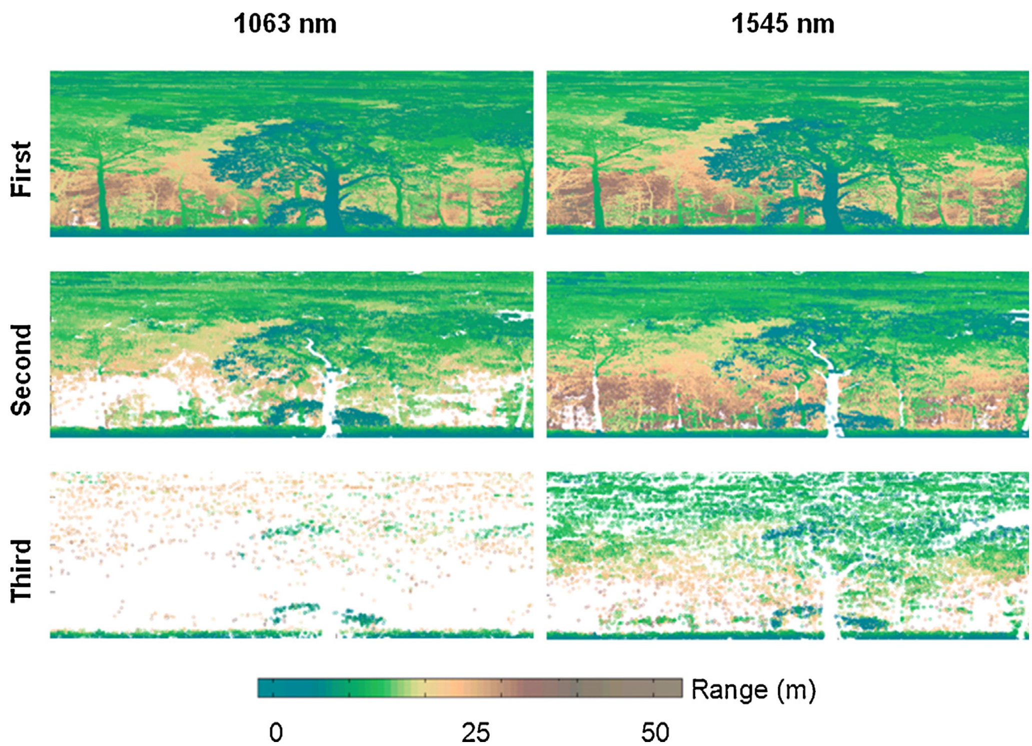

Fig. 3. Dual-wavelength multiple return (first, second, third) point clouds from SALCA scan of an oak/birch plot. Azimuth range 0–180°, zenith range 0–90° and 60 m maximum range recorded (reproduce in colour on web only).

at Delamere Forest was recorded in July 2011 (full leaf cover) and a simple reflectance normalization procedure applied, based on measured maximum return at all ranges to correct for the range-dependent variation in intensity, described in detail in Ramirez et al. (2013). Fig. 4 shows the 1063 and 1545 nm uncorrected intensity images for the plot with dark green indicating high intensity and brown low intensity. The lower figure shows the SALCA Normalized Ratio Index (Eq. (1)) (SNRI) from low (black) to high (bright gray).

$$(\text{SNRI}) = \frac{(\rho 1063 - \rho 1545)}{(\rho 1063 + \rho 1545)} \quad (1)$$

where $\rho 1063$ is the reflectance at 1063 nm and $\rho 1545$ is reflectance at 1545 nm.

The uncorrected images clearly show the effect of range on the return intensities but, after normalization, and application of the ratio, the separation of the woody and leafy material in the SNRI image becomes clearer. At this stage the separation threshold would need to be set interactively but, with more robust calibration and additional information about the spectral properties of the canopy, a threshold could be determined automatically. Work is ongoing to develop routine data calibration procedures for SALCA and ongoing experiments are collecting field spectral measurements to better characterize the reflectance of forest canopy components.

The dual-wavelength measurements of the SALCA instrument also provide an opportunity to explore the use of LiDAR systems to measure vegetation water content. The 1063 nm laser is at a wavelength close to the NIR reflectance peak of healthy vegetation and the 1545 nm laser is on the edge of a major water absorption feature. Passive optical reflectance measurements at wavelengths close to these have often been used to measure leaf and canopy water content from remotely sensed measurements (e.g., Danson et al., 1992; Al-Moustafa et al., 2012). An experiment to test the application of SALCA for measuring leaf water content was conducted in a laboratory setting, using leaves from a range of species, and measuring both laser intensity and leaf water content change over time. Equivalent water thickness (EWT) was estimated from the SNRI with an RMSE of 0.007 g cm^{-2}, based on a leave-one-out cross validation, and the results were consistent with modelled

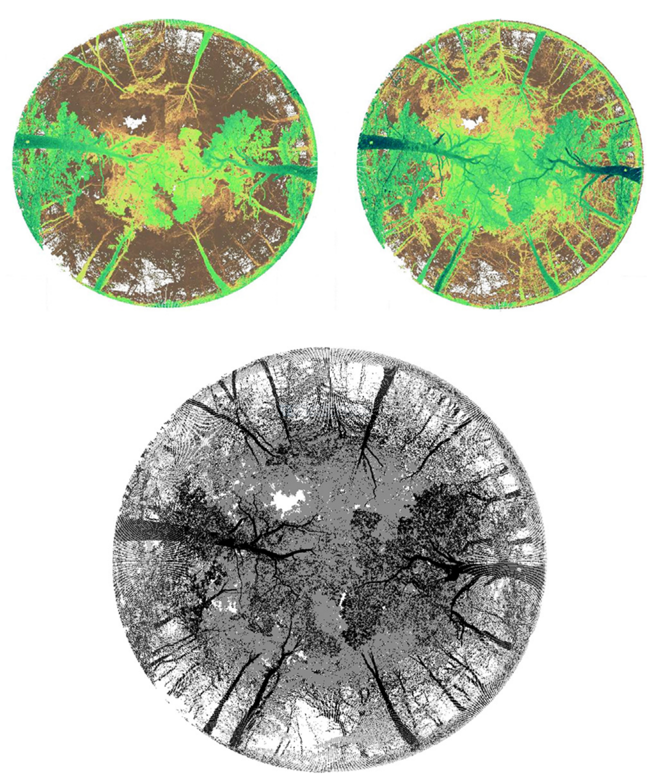

Fig. 4. 1063 (top left) and 1545 nm (top right) uncorrected intensity images of broadleaved deciduous plot with dark green indicating high intensity and brown low intensity, and SNRI (bottom centre) from low (black) to high (light grey) in hemispherical projection (reproduce in colour on web only).

relationships between reflectance and water content from the Prospect model (Gaulton et al., 2013a). Follow-on experiments on complete canopies both in the laboratory and in field experiments have been completed recently and indicate that this measurement capability may be scalable to the canopy level (Gaulton et al., 2013b) opening the possibility of water stress detection in forests using this type of device.

4.3. Reflectance calibration experiments

The key calibration requirement for the applications of SALCA described above is to derive an apparent reflectance product that allows quantitative comparison of the reflectance of objects independent of measurement conditions. TLS reflectance calibration is normally achieved by taking into account the system detector response, the range dependence of intensity measurements, and the optical arrangement of the transmitted pulse with respect to the detector field of view. Since these characteristics are normally system-specific, calibration is most easily achieved using measurements of targets of known reflectance (Kaasalainen et al., 2009). A detailed study to compare the reflectance calibration of five different TLS, including SALCA, is now underway as described in Armston et al. (2013). In this work the TLS measured a six tile multi-reflectance calibration panel at multiple ranges (range (R) = 2, 4, 6, 8, 10, 15, 20, 40 and 60 m) indoors and, in the same scan, an identical target at a range of 8 m. The reflectances of the target were determined using an ASD FieldSpec spectroradiometer equipped with a contact probe. The moving target was used to examine the range-dependent intensity response of the different instruments and the fixed range target was used to determine the intensity–reflectance response and detect temporal changes in recorded TLS intensity. The full outcome of this experiment will be reported in full in the future, but initial results for SALCA are included here. Fig. 5a shows the form of the relationship between range and mean intensity for a single reflectance calibration sub-panel. The form of the relationship is typical for TLS where at close range there is an initial increase in intensity with range, followed by a decrease (Kaasalainen et al., 2009). The form of the relationship at close range is mainly related to the physical offset between the centre of the outgoing beam and the centre of the detector field of view. In the case of SALCA this physical offset is approximately 20 mm, with a small square mirror to steer the beams through the exit aperture located at the edge of a lens to collect the backscattered light and focus it on the detector. In other TLS systems this physical offset may be larger. After a range of 4 m the effects of the inverse square law become more important and at 8 m the relationship approaches the expected $1/R^2$ form.

The intensity–range relationship established using the method illustrated above could be used, with the analysis of additional reflectance panels, to derive a reflectance calibration relationship for the instrument that requires only intensity and range as the input variables. However such a relationship would depend on the existence of a linear relationship between the backscattered energy detected and the reflectance of the object measured. Fig. 5b shows an example of the form of this relationship for a six sub-panel reflectance calibration target at a range of 10 m. The form of the relationship is clearly non-linear so that reflectance calibration will need to take into account the forms of this relationship at all ranges. The observed non-linearity is a characteristic of the detector used and, at higher recorded intensity values, the effects of saturation of the signal. Similar non-linear relationships between recorded DN and reflectance were also found for other TLS tested in this experiment.

These results highlight the complexity of reflectance calibration for systems like SALCA where the range dependence of the intensity measurements does not follow a simple $1/R^2$ function and the relationship between intensity and reflectance is non-linear and

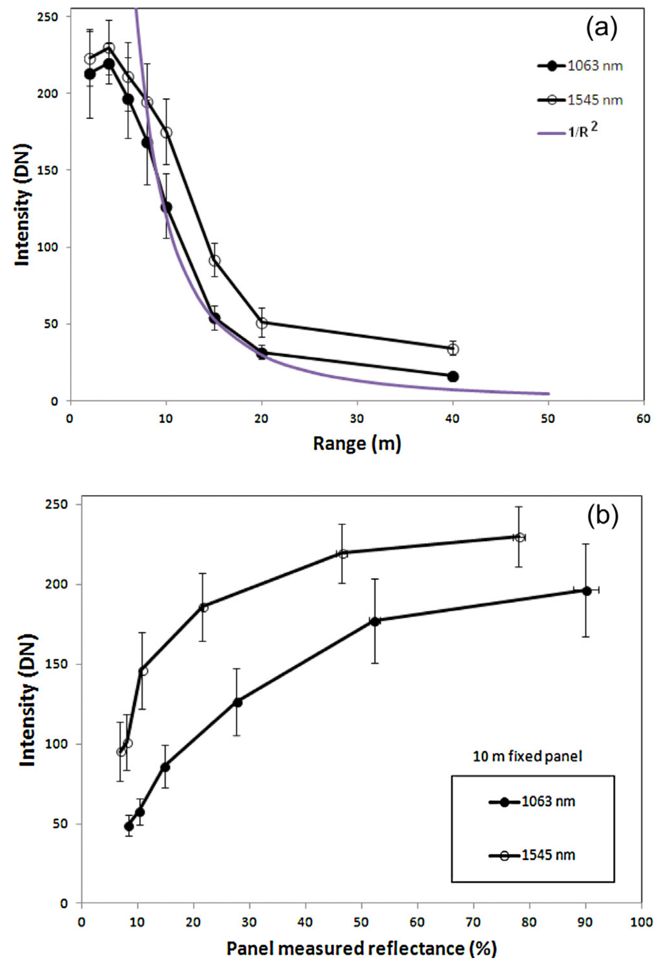

Fig. 5. (a) Mean SALCA intensity for a reflectance calibration panel at multiple ranges. Measured panel reflectance was 21.62% and 27.65% for the 1063 and 1545 nm wavelengths respectively. (b) Intensity–reflectance relationship for six panels at a range of 10 m. Error bars are ± 2 standard deviations.

also range-dependent. In addition, the experiment introduced here showed that there was also time-dependent decrease in measured intensity related to heating of the laser modules, which is possibly influenced by variations in ambient air temperature. A wider range of reflectance panel measurements are now being collected in the field using multiple ranges and under a range of air temperatures to better understand these characteristics of the instrument. These measurements will be used to provide the data to drive a full apparent reflectance calibration for SALCA.

5. Measurement challenges and instrument design

Designing, building and testing a dual-wavelength full-waveform terrestrial laser scanner has provided an opportunity to conduct a range of laboratory and field experiments and to directly explore the instrument characteristics and data properties. Access to the full record of system binary data allows tests to be conducted to assess data processing and information extraction algorithms in a way that is not currently possible with commercial TLS. At the same time this approach has presented a series of challenges related to: accurate reconstruction of the 3D point clouds, which relies on very accurate system timing and a good knowledge of the scanning geometry; accurate beam alignment, which is required to compute band ratios on a point-by-point basis, and must be checked and corrected periodically; and control of the relationship between output laser power and the sensitivity range of the detector, to avoid signal saturation. To address the latter it is currently necessary to use neutral density filters to reduce the laser output power and avoid saturating the detector with returns from close-range high reflectance targets. However, the use of the filters is a trade-off with range, since lower output power reduces the total range over which objects may be detected. Repeat scans in the field, using different filter combinations, has allowed us to explore this issue in detail.

SALCA uses lasers with a short pulse length, narrow beam and small beam divergence so that small gaps in the canopy may be detected (since there will be no return signal); systems with longer pulse lengths and/or larger beam sizes will record more complex waveforms which may be more difficult to interpret. The facility to vary the beam divergence, a feature of the Echidna and DWEL systems, may provide further useful data with which to explore these effects. SALCA's short pulse length limits the accuracy of range detection, as discussed earlier, and so the range accuracy of a single SALCA return using an intensity sum algorithm is likely to be of the order of 2–3 cm. This may limit the application of SALCA for 3D tree reconstruction where sub-centimetre accuracies are ideally required. Range accuracy is partly dependent on object reflectance, and the range at which the object is measured, but we have yet to make a systematic study of these effects. Increasing the signal digitization rate from 1 GHz to 2 GHz would be a simple way to improve SALCA's range measurement accuracy.

There is great potential in the application of dual-wavelength measurements to separate returns from the different canopy components. Using ratios of laser wavelengths should allow separation of canopy components, even when they represent multiple objects intercepting a single laser shot, since the ratios are computed for each return separately. However, it is clear that, unless there is a spectral difference between the woody material and the leaves/needles in a canopy in one of the laser wavelengths, separation of the components will not be possible, and additional laser wavelengths may be required. Where there is a mix of material detected within the same range bin separation will also be difficult. The potential of using multiple laser wavelengths has been demonstrated in laboratory-based studies discussed earlier, and these measurements may provide additional information on 3D canopy biochemistry, although problems associated with the requirement for high laser power and maintaining eye-safe operation in field-based data collection have yet to be overcome.

6. Discussion and conclusions

The Salford Advanced Laser Canopy Analyser is the first dual-wavelength full-waveform TLS designed to measure the three-dimensional characteristics of forest and woodland canopies. It has been deployed in field and laboratory experiments since 2011 and has provided unique data sets with which to assess the potential application of this technology to measure forest canopy biophysical properties. Previous research with commercial single return, or single wavelength TLS has shown that very accurate geometric measurements of forest stand structure can be obtained, but that partial hits, particularly from the canopy, present an insurmountable problem for quantitative data extraction of true LAI. The use of full-waveform multiple wavelength TLS provides a potential solution since they provide information on all objects intercepting the laser beam and measure the spectral properties of different canopy components. Dual-wavelength systems like SALCA represent a significant advance in measurement capabilities, but successful application of the technology for routine measurements of forest canopy dynamics will require accurate system calibration, accurate geometric reconstruction and registration of the scan data in both wavelengths, and development of data extraction algorithms that fully utilize the information recorded.

Acknowledgements

The development and initial testing of the SALCA instrument was funded by a Technology Proof-of-Concept Grant (NE/H002685/1) and a Small Project Grant (NE/I01702X/1) from the Natural Environment Research Council, UK. FMD is currently supported by a Royal Society Leverhulme Trust Senior Research Fellowship (2013–14). The Forestry Commission are acknowledged for permission to undertake fieldwork at Delamere Forest, Cheshire, UK. Dr John Armston and the Terrestrial Laser Scanner International Interest Group are acknowledged for their contributions to the calibration work.

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