Terrestrial laser scanners to measure forest canopy gap fraction

F.M. Danson[1], R.P. Armitage[1], V. Bandugula[1], F.A. Ramirez[1], N.J. Tate[2], K. J. Tansey[2] & T. Tegzes[3]

[1]Centre for Environmental Systems Research, School of Environment and Life Sciences, University of Salford, Manchester M5 4WT, UK
f.m.danson@salford.ac.uk
[2]Department of Geography, University of Leicester, Leicester, LE1 7RH, UK
[3]Infoterra Ltd, Atlas House, 41 Wembley Road, Leicester LE3 1UT, UK

Abstract

The directional gap fraction in forest and woodland canopies is the primary information that is used for the non-destructive estimation of canopy leaf area index (LAI). In this study the directional gap fraction of a mixed species forest stand was measured using three different terrestrial laser scanners providing measurements with two different beam divergences at two different wavelengths. Gap fractions estimated from the laser scanners were compared to the gap fraction derived from hemispherical photographs recorded near simultaneously. The results showed that differences in wavelength gave rise to contrasting intensity images which contained complementary information on canopy composition. Wider beam divergence gave rise to lower estimates of gap fraction, and the terrestrial laser scanners underestimated gap fraction when compared to data derived from the hemispherical photographs. Beam divergence, laser wavelength and range-related variation in intensity all affect gap detection. These issues are discussed and future data processing techniques to provide consistent estimates of canopy gap fraction from terrestrial laser scanners are discussed.

Keywords: terrestrial laser scanner, gap fraction, forest canopy

1. Introduction

There has been an explosion of research examining the interaction of airborne laser scanner (ALS) data with forest and woodland canopies (see Omasa *et al.,* 2007 for a recent review), and some significant advances in measuring and modelling these interactions have been made over the last decade (Nilsson 1996;. Hyyppä *et al*. 2001; Næsset 2004). ALS provide both spatial and spectral (intensity) data on vegetation properties and the laser scanner data may be related to canopy cover or leaf area index, or may be used to estimate canopy height and crown shape (Koetz *et al*. 2006; Morsdorf *et al*. 2004; Hopkinson and Chasmer, 2007). In contrast to ALS, terrestrial laser scanners (TLS) have the advantage of higher point density, rapid and cheap deployment and multi-angular sampling capability. These features make TLS suitable for point or plot-based surveys of forest structure, and potentially an information source for validating ALS data collected for the same sites.

There are relatively few studies that have used TLS to measure vegetation structure despite the advantages indicated above. Most of the studies published to date using TLS have focussed on the measurement of forest stand variables, including tree height, stem taper, diameter at breast height and planting density (e.g., Hopkinson *et al*. 2004; Thies *et al*. 2004; Watt and Donoghue 2005; Henning and Radtke 2006a). A small number of studies have attempted to use TLS for characterizing canopy variables like leaf area index, canopy cover and the vertical distribution of foliage, and a notable early contribution was the work of Tanaka *et al*. (1998) who coupled a laser source and a digital CCD camera to measure foliage profile in vegetation canopies. The system was developed to use two different laser wavelengths to map the woody and green material in the canopy (Tanaka *et al*. 2004). Radtke and Bolstad (2001) used a laser range finder to conduct a point quadrat survey in order to determine vertical foliage profile in a broad-leaved forest. LAI estimates from the laser survey were not significantly correlated with LAI derived from litter fall surveys however, and problems with such hand-held systems were highlighted. Lovell *et al*. (2003) used a tripod-mounted laser scanner to determine directional gap fraction in woodland stands of different species and found close correlation with data from hemispherical photography. They also successfully estimated LAI of the stands by using gap fraction data. Henning and Radtke (2006b) tested the application of a TLS to measure a wide range of variables in mixed species broad-leaved woodland and published the first comparisons of single site multi-temporal TLS data for vegetation canopies. Estimation of plant area index and LAI was based on the computation of laser hits within voxels of 0.5m. More recently, a TLS voxel-based approach to the calculation of leaf angle distribution to derive LAI was adopted by Hosoi and Omasa (2007).

Most ALS studies to estimate LAI and canopy cover have been based on the assumption that the ratio of ground returns to total returns is equivalent to the gap fraction in the zenith direction. TLS have the advantage of sampling canopy gap fraction in multiple directions and in this case a Poisson model may be used to derive LAI. With TLS it is the ratio of total laser shots in a given direction to laser shots with a return signal above the noise threshold in the same direction that yields gap fraction estimates; this is are likely to provide more accurate estimates of LAI than the vertical sampling of an ALS.

Wagner *et al.* (2006) developed a special form of the radar equation to compute the return power of a laser pulse for a given geometric setting, in which they introduce the cross-section of the scatterer:

$$P_r = \frac{P_t D_\gamma^2}{4\pi R^4 \beta_t^2}\sigma \tag{1}$$

Where P_r is the power at the receiver, P_t the laser pulse energy at the transmitter, D_r is the aperture diameter of the receiver optics, R the distance between the laser and the target, β_t is the beam divergence and σ is the backscatter cross-section, defined as:

$$\sigma = \frac{4\pi}{\Omega}\rho_s A_e \tag{2}$$

Where Ω is the angle defining a backscattering cone due to surface roughness, ρ_s is the reflectivity of the scatterer and A_e is the illuminated area of the scattering element. From Equation 1 we can see that, for a given TLS, the beam divergence, pulse energy and receiver optics are fixed, and so return power depends on range, target reflectivity and the area of the target within the beam. The return power required to record a laser ‘hit’ also depends on the way in which the instrument analyses the return waveform. Target detection uses a threshold signal above the instrument noise and this threshold may be fixed or depend on a function related to the peak amplitude of the return intensity. A further issue is that target detection will also depend on the wavelength of the laser, since the return signal depends on target reflectivity. Hence, a target with low reflectance may not be detected at the same range as one with a higher reflectance. The objective of this research was to explore these relationships by comparing the directional gap fraction measured at a single forest plot using three different TLS with two different beam divergences, and two different wavelengths.

2. Methods

The study area was Martinshaw Wood, located 10km NW of Leicester, UK at British National Grid reference SK510072. The woodland consists of 102ha of mixed species stands owned and managed by the Woodland Trust. The stand used for the measurements consisted of an overstorey dominated by Corsican Pine with Scots Pine and Oak, and an understorey of Hazel, Sycamore, Birch, Hawthorn and Goat willow. Three different Riegl™ TLS (Table 1) were used to collect data following the methodology of Danson *et al*. (2007a), where the laser scanners were mounted on a tripod at a height of 1.5m and oriented to scan in hemispherical mode over a zenith angle range of -90° to +90°, using the full 80° field of view of the instruments. Two orthogonal scans were recorded so that most of the hemisphere was imaged by the two scans; gap fractions from the two orthogonal scans were later averaged. The angular sampling resolution was set to 0.108° with all instruments recording the 'last return' only. A single scan consisted of approximately 1.2 million points and each point was recorded as a set of x, y, z and intensity values. The complete set of measurements (3 TLS × 2 scans) was completed within approximately 50 minutes. A Nikkon digital SLR fitted with a hemispherical lens was mounted on the tripod and levelled, and two orthogonal photographs taken. This lens provides a 180° field of view across the image diagonal and the two orthogonal images were later merged to form a single image of approximately 9 megapixels covering most of the hemisphere (Figure 1).

Table 1: Technical comparison of terrestrial laser scanners used

Riegl model	Beam divergence	Wavelength	Angular step sampling	Maximum range ρ>80%
LMS-Z210i	2.7 mrad	900nm	0.108°	650m
LMS-Z390i	0.3 mrad	1550nm	0.108°	400m
LMS-Z420i	0.27 mrad	1550nm	0.108°	1000m

To compute the directional gap fraction for the laser scanner data the number of 'hits' (laser shots with measured echo) in 5 degree zenith bands (0-4.9, 5-9.9, etc.) was computed by comparing the measured data with the expected number of 'shots' in the same zenith bands, derived from a model which takes into account the scan geometry and angular step sampling of the scanners (Danson *et al*. 2007a). The ratio of hits to shots was used to derive the average canopy gap fraction in a given zenith band. The hemispherical photographs were analysed using the Gap Light Analyzer software (Frazer *et al.* 2000) with different thresholds to differentiate the canopy from the sky.

Figure 1. Merged hemispherical photographs of canopy. Red circle shows the position of the horizon and illustrates the area of the hemisphere not imaged.

3. Results

Simple visualisation of the laser scanner data showed the striking difference in intensity values caused by differences in laser scanner wavelength (Figure 2). The Z210i data show low intensity for the tree stems and branches and higher intensity for dense areas of foliage. In contrast the Z390i and Z420i scans show high intensity for the tree stems and relatively lower intensity for the foliage. There is also evidence in Figure 2 that the Z210i 'sees' fewer gaps in the canopy than the other two TLS. It should be noted that cross comparison of the intensity values between the intensity images from the three scanners is not advisable since the intensity data are not cross-calibrated between the scanners.

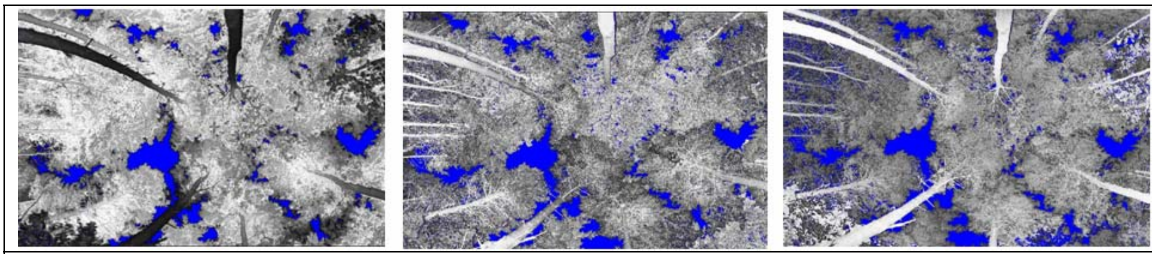

Figure 2. Intensity images of forest canopy in cylindrical projection from Z210i (left), Z390i (middle) and Z420i (right). Sky gaps are blue.

The canopy directional gap fraction computed from the three laser scans showed a similar pattern with a very low gap fraction at zenith angles between 0° to 20°, maximum gap fractions of approximately 13% at zenith angles between 25° to 30° and lower gap fractions at higher zenith angles. The Z210i data showed a 2-3% lower gap fraction across all zenith angles; the Z390i and Z420i showed very similar gap fractions up to 35° and thereafter the Z420i showed a 3-4% larger gap fraction (Figure 3).

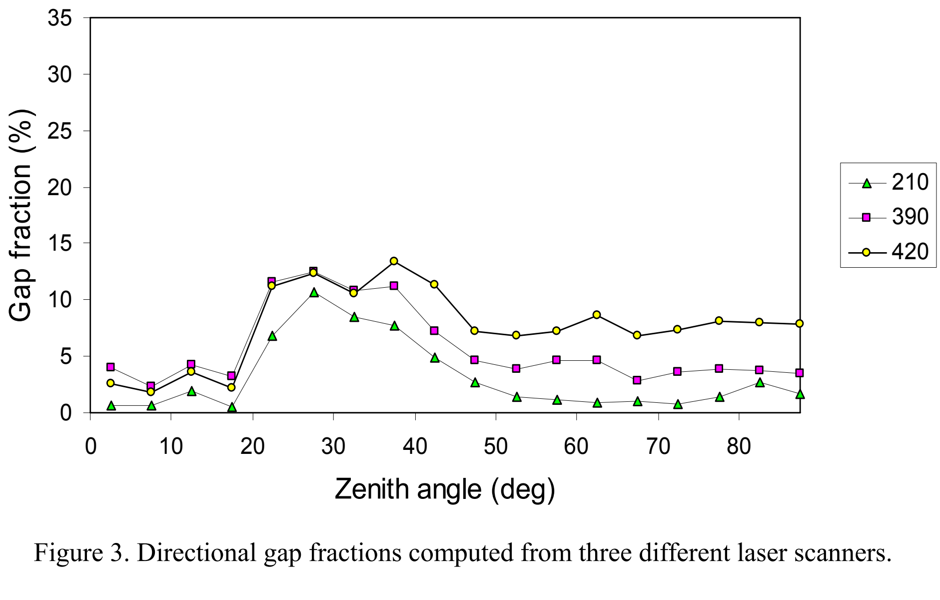

Figure 3. Directional gap fractions computed from three different laser scanners.

Comparison of the gap fraction computed from the laser scanners and the hemispherical photographs showed large differences in the magnitude and shape of the gap fraction distributions (Figure 4). Gap Light Analyzer allows different threshold to be applied to separate sky and non-sky elements. Using an automatic threshold of 128 (T128) produced a maximum gap fraction of 26% compared to 13% for the Z390i. Using a higher threshold (T200) which reduced the sky fraction in the photographs resulted in a lower gap fraction, closer in magnitude to that of the laser scanner data, but again different in shape (Figure 4).

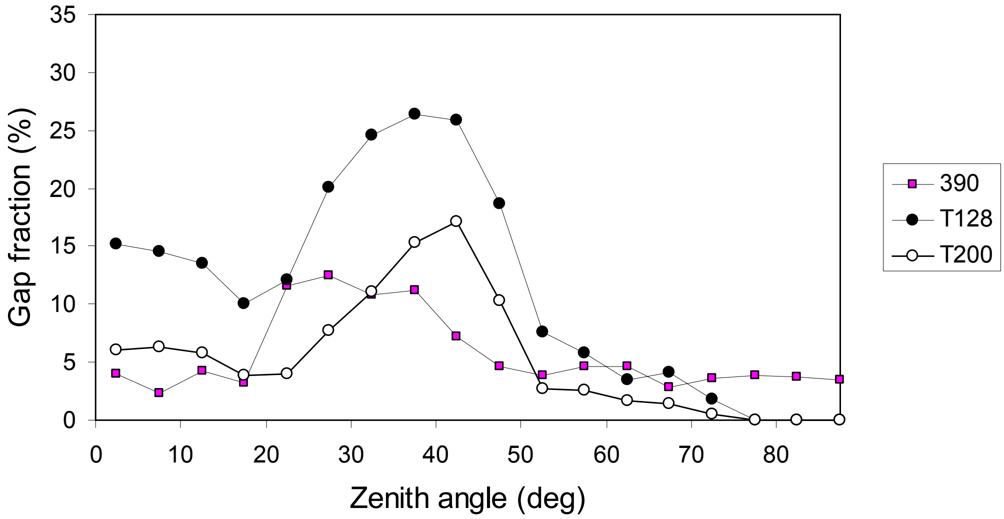

Figure 4. Comparison of gap fraction derived from Z390i laser scanner, and hemispherical photographs with two different thresholds (T128 and T200)

4. Discussion

The variations in intensity in the laser scanner data (Figure 1) are related to differences in the reflectance properties of the scattering elements. At a laser wavelength of 900nm (Z210i) the reflectance of vegetation is greater than the reflectance of the tree stems, since this is the wavelength region of greatest scattering and lowest absorption for green vegetation. In contrast, 1550nm (Z390i and Z420i) is a region of water absorption for vegetation and it is likely that the green vegetation has a lower reflectance than the tree stems. These spectral contrasts provide an opportunity for classification of laser data, according to intensity, in order to separate woody and green material using multiple wavelengths. Two factors add complexity here however, first, where the scattering elements do not fully occupy the laser beam, a lower intensity may be recorded and this may be interpreted as comprising objects with lower reflectance, second, we have identified a range-dependent variation in intensity which is related to the scanner optical system rather than to the physics of the radar equation (Danson et al., 2007b). It will be necessary to characterize and correct this variation before the intensity data can be properly interpreted. It will also be necessary to examine the directional reflectance properties of forest canopy targets since the return intensity is also affected by variation in target bidirectional reflectance distribution function.

The differences in measured canopy directional gap fraction between the three laser scanners are primarily related to differences in beam divergence. The Z210i produces a beam that is 30mm wide at 10m range whereas the Z390i and Z420i produce beams which are 3mm and 2.7mm wide at 10m range respectively. The Z210i therefore does not 'see' the smaller gaps in the canopy because the probability of a scattering element appearing within the wider beam is greater. The directional gap fraction measured by the Z390i and Z420i, with similar beam divergence, is very similar up to the 35-40° zenith band, but the higher gap fraction for the Z420i at larger zenith angles is difficult to explain. The Z420i has a much longer range and slightly narrower beam than the Z390i and these may affect the echo detection characteristics; further investigation and experimentation of this point is clearly required. It may also be the case that the Z420i was measuring a slightly different part of the canopy since no attempt was made to accurately co-locate the scans from the three instruments.

The difference in directional gap fraction estimates from the laser scanner data and the hemispherical photography is striking and we hypothesise that it is related to the way in which pulses are detected by the laser scanners. Small objects, occupying a small proportion of the area of the beam, appear to be detected by the laser scanners. If gaps occupying less than 50% of the laser beam are detected by the laser scanner then this will lead to an underestimation of the gap fraction. We have experimented with filtering the laser scanner data to remove points with low intensity hypothesised to correspond to larger gaps. Removal of these points increases the gap fraction estimates but the range-related intensity variation mentioned earlier must be addressed before this approach can be properly tested.

5. Conclusions

Terrestrial laser scanners have the potential to revolutionise the measurement of vegetation canopy structure. However, commercially available instruments are primarily designed to measure ‘hard’ objects like buildings and terrain. The application of this technology to measure soft targets like vegetation canopies presents some real challenges of data collection, data interpretation and modelling. Comparisons with hemispherical photographs are useful since such data have been used to measure forest canopy gap fraction for many years. It is clear however that further data processing will be required before the measurements converge. Further research is required to explore the use of intensity data in the calculation of gap fraction, to address some of the issues identified above. It is clear that intensity calibration will be vital if we are to use this information to improve gap fraction calculations. A better understanding of the interactions of TLS with vegetation canopies should yield new methods for characterising forest and woodland canopies and provide a practical way of validating studies undertaken with ALS data.

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