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Measurements of land surface features using an airborne laser altimeter: the HAPEX-Sahel experiment

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Abstract. An airborne laser profiling altimeter was used to measure surface features and properties of the landscape during the HAPEX-Sahel Experiment in Niger, Africa in September 1992. The laser altimeter makes 4000 measurements per second with a vertical resolution of 5 cm. Airborne laser and detailed field measurements of vegetation heights had similar average heights and frequency distribution. Laser transects were used to estimate land surface topography, gully and channel morphology, and vegetation properties (height, cover and distribution). Land surface changes related to soil erosion and channel development were measured. For 1 km laser transects over tiger bush communities, the maximum vegetation height was between 4·5 and 6·5 m, with an average height of 2·1 m. Distances between the centre of rows of tiger bush vegetation averaged 100 m. For two laser transects, ground cover for tiger bush was estimated to be 22·5 and 30·1 per cent for vegetation greater than 0·5 m tall and 19·0 and 25·8 per cent for vegetation greater than 1·0 m tall. These values are similar to published values for tiger bush. Vegetation cover for 14 and 18 km transects was estimated to be 4 per cent for vegetation greater than 0·5 m tall. These cover values agree within 1–2 per cent with published data for short transects (< 100 m) for the area. The laser altimeter provided quick and accurate measurements for evaluating changes in land surface features. Such information provides a basis for understanding land degradation and a basis for management plans to rehabilitate the landscape.

1. Introduction

Topography and land surface features (i.e., vegetation, soil roughness) influence the functions of natural and agricultural landscapes. Measurements of land surface shapes and patterns provide data to understand changes in land surface patterns in space and time. Measuring these features and their spatial patterns using conventional technologies provide only limited temporal and spatial data.

Applying laser range finding technology from an airborne platform provides a rapid and accurate measurement of land surface topography and roughness features and patterns. Airborne laser surveys have been used to measure vegetation properties (Schreier *et al.* 1985, Nelson *et al.* 1988, Ritchie *et al.* 1992, 1993 a), erosion and stream features (Ritchie and Jackson 1989, Ritchie *et al.* 1993 b), topography (Krabill *et al.* 1984), and aerodynamic roughness (Menenti and Ritchie 1992, 1994). Surface features of the Earth and other planets have been measured from lasers on satellites (Bufton 1989, Seshamani 1993).

An airborne laser altimeter was used to measure profiles of land surface features and patterns during the HAPEX-Sahel Experiment in Niger, Africa in September 1992. This paper discusses the application of this laser data for making vertical measurements of features and patterns of the land surface and discusses their applications to understanding the interactions of land surface roughness, hydrological systems, vegetation patterns, and energy fluxes on natural and agricultural landscapes at the HAPEX-Sahel study sites.

A second purpose of this paper is to compare airborne laser data with detailed field measurements. Such a comparison is difficult since the laser altimeter system measures a very narrow strip (footprint is 6 to 15 cm wide) of the land surface. Even then the laser beam can reflect from targets smaller than the footprint thus triggering the receiver (timer) in the instrument and measuring the aircraft-to-object range. This has been observed in the studies of agricultural and natural vegetation (Ritchie *et al.* 1992, Menenti and Ritchie 1994). The comparison of laser measurements with field data is also challenging because of the difficulty of co-locating field and laser observations on the same 6 to 15 cm path and reproducing the laser observations, given the horizontal resolution of the laser.

2. Study area

This study was part of the HAPEX-Sahel (Hydrologic and Atmospheric Pilot Experiment in the Sahel) Experiment. One objective of the HAPEX-Sahel study was to use remote sensing techniques to measure land surface processes in relation to water and energy fluxes as a function of land change (degradation). The HAPEX-Sahel study site was a 1° × 1° area located at 2°–3° E, 13°–14° N in the West African Sahel region of West Niger. Niamey, Niger, is located at the western edge of the study site. Within this larger study area, three smaller study sites were established. Intensive ground and remote sensing data were collected in August and September 1992. These three smaller areas were designated Southern, West Central, and East Central super sites. Laser altimeter data were collected at the three super sites. Prince *et al.* (1995) give a detailed description of the purposes, study sites, and data collected during the HAPEX-Sahel Experiment.

3. Methods and materials

The U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS) laser profiling altimeter mounted on a National Aeronautics and Space Administration (NASA) C-130 airplane was used to measure land surface features at the HAPEX-Sahel super sites (Southern, West Central and East Central) in September 1992. Laser data collected along six flight lines (table 1) on 12 September, 1992, over the West Central and East Central super sites were used for this paper.

Laser distancing technology is based on generating short duration (nanoseconds) laser pulses that are transmitted toward a target (landscape surface). A target is defined as any object that reflects back the light pulse (or part of the light pulse) and triggers the receiver. The receiver measures the lapse time between pulse initiation and its return. Highly accurate timing (less than a nanosecond) is required. For example, 1 ns timing allows an accuracy of approximately 30 cm vertical resolution for each measurement. Time is converted to distance using the velocity of light. Laser pulse width and timing electronics determine vertical resolution. Current timers allow the determination of surface topography with a vertical resolution of less than 5 cm.

Table 1. Location of the laser flight lines used in this study.

Laser dataset	NASA C-130 designation	Start latitude (N)	Start longitude (E)	End latitude (N)	End longitude (E)
Nig92-13.dat	892 line 1 run 1	13° 32·4′	002° 29·3′	13° 32·3′	002° 45·5′
Nig92-14.dat	892 line 1 run 2	13° 31·8′	002° 45·7′	13° 32·1′	002° 30·0′
Nig92-15.dat	892 line 3 run 1	13° 32·5′	002° 29·3′	13° 32·6′	002° 45·1′
Nig92-23.dat	892 line 13 run 1	13° 34·6′	002° 34·3′	13° 29·7′	002° 33·8′
Nig92-24.dat	892 line 14 run 1	13° 30·2′	002° 32·2′	13° 30·2′	002° 36·1′
Nig92-25.dat	892 line 14 run 2	13° 30·1′	002° 39·1′	13° 30·0′	002° 34·3′

The laser altimeter used in this study is a pulsed gallium–arsenide diode laser, transmitting and receiving 4000 pulses per second at a wavelength of 0·904 μm (table 2). Power constraints of the laser altimeter system limit the altitude (distance that can be measured) of the airplane to approximately 300 m. Nominal ground speed of the C-130 during the flights was 75 m s^{-1}. Under these operating conditions, a laser measurement of distance from the airplane to the land surface occurred at sampling intervals of 1·875 cm along the flight line. The beam divergence of the laser is 0·6 maad that gives a 'footprint' on the ground that is approximately 0·06 per cent of the altitude (or approximately 12 cm for the nominal 200 m altitude used during these flights). The timing electronics of the laser receiver allow a vertical resolution of 5·0 cm for a single measurement to be recorded.

Digital data (distance from the laser on the C-130 to the land surface) from the laser receiver are recorded directly to the hard disk of a portable computer. Data from a gyroscope and an accelerometer mounted on the base of the laser platform are recorded simultaneously (60 times per second) and used to correct for airplane

Table 2. Specifications of the airborne laser profiling system.

Laser transmitter	
Laser type	Gallium Arsenide Semiconductor Diode
Pulse width	20 ns
Pulse energy	117 mJ
Wavelength	0·904 µm
Beam divergence	0·6 mrad (collimated)
Pulse rate	4000 pulses s^{-1}
Laser receiver	
Field-of-view	2·5 mrad
Wavelength	0·904 µm
Bandpass	0·020 µm
Receiver detector	Silicone avalanche photodiode
Detector size	1·77 mm^2
Responsivity of detector	34 A W^{-1}
Vertical resolution	$\pm$5 cm, single shot measurement

motion in the laser data. A video camera, borehole-sighted with the laser, records an image of the flight line. Sixty video frames are recorded per second. Each frame is annotated with consecutive numbers and the C-130 clock time. Each video frame number is recorded with the digital laser data by the computer to allow precise location of the laser data on the landscape with the video and the C-130 data. The C-130 clock time allows the location of the laser flight line to be determined using the C-130 flight and GPS (Global Positioning System) data.

Land surface elevation was calculated for each laser measurement using known elevations along a flight line. The minimum elevations (maximum laser measurements between C-130 and the land surface) along a flight line are assumed to be ground surface elevation with measurements above these minimums being due to vegetation or man-made structures.

A simple field system was designed to make detailed field measurements to evaluate the accuracy of the airborne laser measurements. The field sampling system consisted of:

(i) Three plexiglass probes 2 m long with diameters of $\varnothing = 0{\cdot}5$, $1{\cdot}0$ and $2{\cdot}0$ cm were marked in increments of 1·0 cm. A 0·25 m section of the thinnest probe ($\varnothing = 0{\cdot}5$ cm) was mounted on the lower end of a 1·75 m long probe having $\varnothing = 1{\cdot}0$ cm.
(ii) A rail (2 m long) with $\varnothing = 1{\cdot}0$ cm holes spaced 2·0 cm, centre to centre, was used to position the plexiglass probes ($\varnothing = 0{\cdot}5$ and $1{\cdot}0$ cm).
(iii) A rail (2 m long) with $\varnothing = 2{\cdot}0$ cm holes spaced 4·0 cm, centre to centre, was
(iv) used to position the $\varnothing = 2{\cdot}0$ cm plexiglass probe.
Removable supports at the ends of the rails allowed the rail to be placed above canopies at any height between 0 and 2 m.

Vegetation heights along the ground transects were measured by sliding the probes vertically through the corresponding horizontal rail and recording the distance to the first hit of a land surface element (vegetation or soil). The rail with the 1·0 cm holes was used for the 0·5 and 1·0 cm probe, then removed and substituted with the 2·0 cm rail. Marks were placed on the ground to position the second rail to overlap the first one. Field measurements with probes of different diameters were done sequentially with each 2 m segment. Measurement differences between probes would be due to probe diameters, probes tilted slightly off-nadir, and the effect of wind moving leaves and stems, making it likely that different probes would hit different plant elements.

Field measurements were collected along two lines (10 to 20 m long) at three sites. Field site 1 was in a millet (*Pennisetum glaucum* L. R. Br.) field at the south end of the N–S transect east of the town of Fandou Beri (East Central super site). Field site 2 was in a clearing with herbaceous vegetation located along the same N–S transect east of Fandou Beri. Field site 3 was in a fallow field at the West Central super site. Fallow was defined in the context of HAPEX-Sahel as an abandoned agricultural area where shrubs dominate. The video data collected during the laser flights were used to locate positions of the field study sites along the laser flight line. However, comparisons of laser and field measurements are only meaningful when done in terms of statistics results since it is not possible co-locate airborne laser measurements and field measurements on the same line.

The basic approach to analysing laser data is to study land surface elements using the frequency distribution of objects hit by the laser beam and their height above the ground. Profiles of ground elevation are obtained from the laser measurements as the lower envelope (minimum measurement) of the actual detailed laser measurements.

For vegetation and land surface studies, the parameters determined are fractional vegetation cover, leaf area index, and surface roughness. All these measurements are derived from the frequency distribution of objects hit by the laser beam and their height above the ground. Research on laser measurements in the framework of the HAPEX-Sahel Experiment was focused on the experimental validation of the frequency distribution observed with the laser and with detailed ground measurements. Random noise in the field and laser measurements was removed using the procedure described by Menenti and Ritchie (1994).

4. Results and discussion

Many objects (i.e., soil, rock, vegetation, man-made structure) on the land surface reflect the laser pulses (Ritchie and Jackson 1989) and are measured to define a vertical land surface profile. Measurements of land surface features and patterns made at the HAPEX-Sahel West Central and East Central super sites are used to provide examples of the different land surface features and properties (i.e., topography, vegetation covers and densities, surface roughness) extracted from the airborne laser altimeter data. Locations of the flight lines are given in table 1. Field measurements for comparison with the laser data were collected along flight lines Nig92-15 and Nig92-23.

5. Accuracy and validation

Under controlled laboratory conditions, the standard deviation of laser measurements of a stationary flat surface is 0·11 m and is constant for distances between 50 and 300 m. Signals due to random and system noise associated with system electronics contributes to the standard deviation measured under both controlled laboratory and field conditions. Mathematical filters (i.e., moving averages, block averages) are used in the analyses to reduce the random and system noise signals and enhance the systematic variation due to the land surface features in the laser data (McCuen and Snyder 1986).

The choice of the number of measurements to be used for a moving average filter or other types of filters to reduce random and system noise and to enhance the systematic variations in the laser data is not a simple matter. If the macro-change in topography as defined by a line connecting the minimum laser values is subtracted from the laser measurements, then a profile of surface roughness plus system and random noise is defined. Standard deviations of this derived profile as a function of number of measurements in a moving average filter were calculated. A plot (figure 1) of the standard deviations as a function of the number of measurements in a moving average filter using 8000 laser measurements for the profile shown in figure 5 shows an exponential decrease in the standard deviation as the number of measurements averaged increased. The standard deviation for these laser measured field data (8000 measurements) was 0·140 m. Under controlled laboratory conditions, the standard deviation of laser measurements (50 000 measurements) of a stationary flat surface was 0·11 m. The difference in standard deviations between field (0·14 m) and laboratory (0·11 m) measurements would be due to surface roughness and reflectivity of the targets (land surface versus flat laboratory target), the stability of the platforms (C-130 versus laboratory bench), and atmospheric conditions. If the errors in the

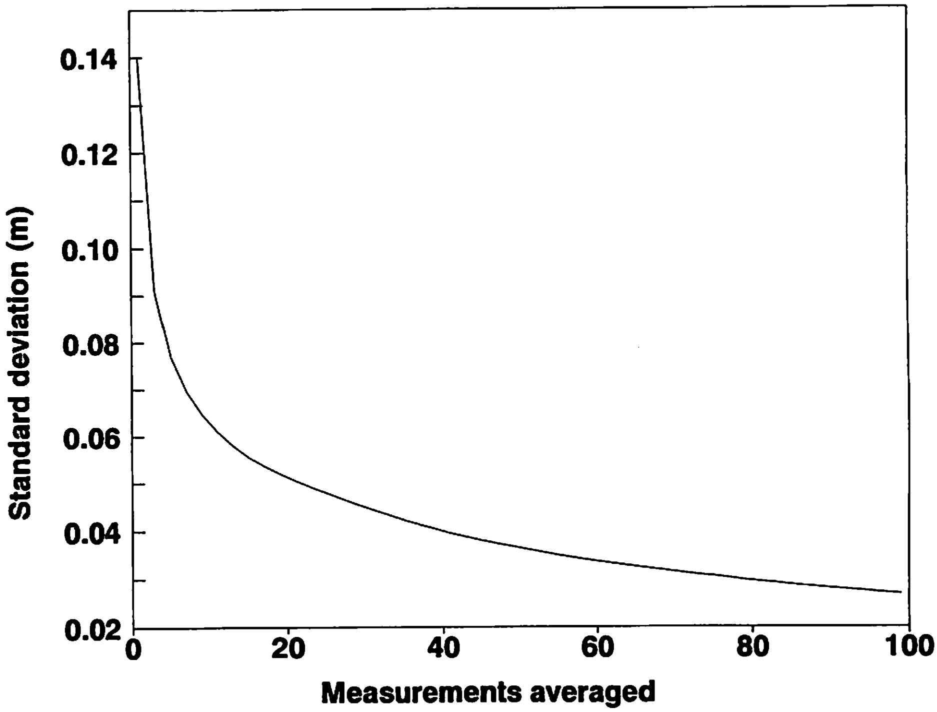

Figure 1. Plot of standard deviations of the laser data as a function of the number of measurements averaged. Laser data profile used is shown in figure 5.

laser measurements are assumed to be random, then an expected standard deviation can be calculated by dividing the vertical laser resolution (0·05 m) by the square root of the number of measurements averaged. Using an 11-measurement moving average, the calculated standard deviation for the 8000 measurements was 0·061 m. The standard deviation for a moving average of 21-laser measurements was 0·050 m which is the vertical resolution of the laser. If it is assumed that the curve in figure 1 has two components (a steep negative slope and shallow negative slope) and fit straight lines to these two slope components, the intersection of these two lines occurs between 9 and 13 measurements depending on the beginning and ending points used. Based on these analyses of the change of slopes, an 11-measurement moving average was used in the analyses in this paper.

For the field measurements, the effect of the horizontal resolution (footprint) as measured by different probe diameters (0·5, 1·0, 2·0 cm) on the ground was evaluated first by comparing field measurements of mean vegetation height and the frequency distribution of height observed at field sites 1, 2 and 3 for all lines and resolutions (figure 2). The shift in observed frequencies towards greater vegetation height with increasing probe diameters agrees with the concept that a larger probe is less likely to penetrate the canopy than smaller probes.

The field data (tables 3 and 4) show that the effect of horizontal resolution is limited for the vegetation at site 2 but significant for site 3. The effect of resolution depends on vegetation density and leaf size (Wilson 1963, Stewart and Dwyer 1993). The largest probe is slightly less likely to penetrate the canopy at site 2 but is significantly less likely to penetrate the canopy at site 3. The 1·0 cm probe (table 3)

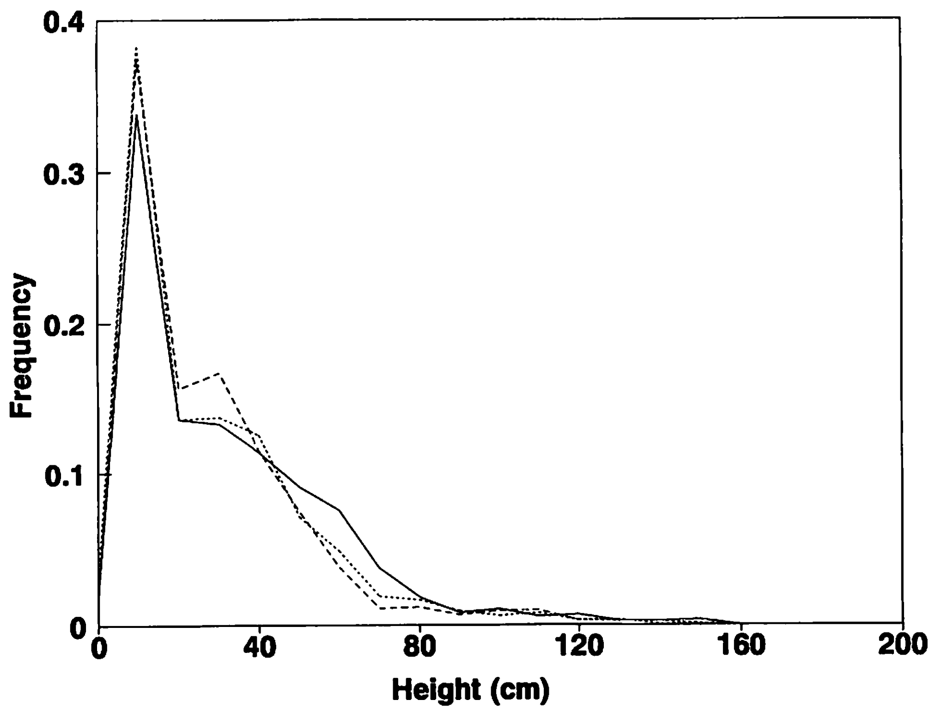

Figure 2. Frequency distribution of vegetation heights for all sites and lines obtained with field measurements for each horizontal resolutions (------ 0·5 cm, ——— 1·0 cm, —— 2·0 cm) have been merged.

Table 3. Field measurements of vegetation height at site 2 located along the N–S transect east of the town of Fandou Beri. Profiles measured along two lines using three probes of diameters $\varnothing = 0{\cdot}5$, 1·0 and 2·0 cm. In each data set h_x is maximum vegetation height, $\bar{h}_x$ is mean vegetation height and σ_h is the standard deviation.

Site description	$\varnothing$ (cm)	h_x (cm)	$\bar{h}_x$ (cm)	σ_h (cm)
Site 2 line 1	0·5	86·4	18·2	15·6
	1·0	81·3	18·8	16·1
	2·0	87·1	20·4	16·5
Site 2 line 2	0·5	76·0	26·5	15·8
	1·0	82·2	28·1	16·1
	2·0	107·0	27·6	16·8

penetrated deeper (lower h_x) in the canopy than either the 0·5 cm or the 2·0 cm probe. This is likely to be due to the effect of wind on the canopy. Field measurements with probes of different diameters were not done simultaneously. The three probes were used sequentially for each 2 m segment. Probes could tilt slightly off-nadir at times and, more importantly, the effect of wind could not be eliminated, so that leaves and stems were moving at times, making it likely that different probes would hit different plant elements. Given the large number of ground measurements this problem was not critical for the determination of mean vegetation height or the frequency distribution, while it may have significant effects on the estimation of maximum vegetation height as shown by the h_x values in table 3. We believe that the comparison of laser

Table 4. Field measurements of vegetation height at site 3 located in the clearing near study site 2a at the West Central super site. Profiles measured along two lines using three probes of diameters $\varnothing = 0{\cdot}5$, 1·0 and 2·0 cm. In each data set h_x is maximum vegetation height, $\bar{h}_x$ is mean vegetation height and σ_h is the standard deviation. (*) A shorter segment only was measured with the 0·5 cm probe due to mechanical failure.

Site description	$\varnothing$ (cm)	h_x (cm)	$\bar{h}_x$ (cm)	σ_h (cm)
Site 3 line 1	0·5	120·0	14·8	15·0
	1·0	128·0	20·1	17·5
	2·0	131·0	24·7	19·1
Site 3 line 2	0·5*	39·0	13·9	9·4
	1·0	88·5	23·8	20·1
	2·0	81·7	26·8	21·0

and field measurements is only meaningful when done in terms of statistics. Leaf-size measurements were not available to address this issue more precisely. Ground measurements made at site 1 are not used further in this paper because of the sparseness of the vegetation (millet) and the high spatial variability of the vegetation made comparison with the laser data questionable. The overall similarity of the frequency distribution in figure 2 and the consistency of the observed differences with the probe sizes used indicates that the number of measurements is sufficiently large to eliminate artifacts likely to affect samples of much smaller size.

Short segments of laser data collected at the three field study sites were extracted for comparison with the field measurements. For each site mean vegetation height and standard deviation are presented (tables 5 and 6) for these laser segments to illustrate spatial variability. The data show that variability of vegetation height may

Table 5. Laser measurements of vegetation height at field site 2 located along the N–S transect east of the town of Fandou Beri. Laser measurements are subdivided into four segments to illustrate spatial variability; in each dataset h_x is maximum vegetation height, $\bar{h}_x$ is mean vegetation height and σ_h is the standard deviation. For each segment the position of the data points included in the subset is indicated. Skipped data points covered shrubs and trees not included in the field measurements.

Site description	Segment	h_x (cm)	$\bar{h}_x$ (cm)	σ_h (cm)
Site 2	0–1000	77·5	26·7	13·9
	1501–3000	163·0	34·0	24·0
	3301–4500	72·0	27·0	14·2
	4501–6001	74·5	27·4	13·9

Table 6. Laser measurements of vegetation height at field site 3 located in the clearing near study site 2a at the West Central super site. Laser measurements are subdivided into three segments to illustrate spatial variability. Line 1 at this site (see table 3) is located in segment 2 and 3. In each data set h_x is maximum vegetation height, $\bar{h}_x$ is mean vegetation height and σ_h is the standard deviation.

Site description	Segment	h_x (cm)	$\bar{h}_x$ (cm)	σ_h (cm)
Site 3	0–1500	95·8	34·7	15·9
	1501–3000	90·0	26·9	13·6
	3001–4500	95·0	25·3	14·0

be significant even within homogenous vegetation cover. This is illustrated by segment (1501–3000) in table 5 and segment (0–1500) in table 6.

The closest approximation to co-located field and laser measurements was obtained for site 3, particularly line 1 (table 4) and the laser segments 1501–3000 and 3001–4500. Error in co-location for the laser profile and the field measurements was less than 5 m. Comparisons of mean vegetation height (h_x) for this case gave:

$$\text{Laser} \qquad \bar{h}_x = 26{\cdot}1 \pm 17{\cdot}6\,(\text{cm})$$

$$\text{Field (average)} \qquad \bar{h}_x = 19{\cdot}9 \pm 26{\cdot}6\,(\text{cm})$$

The range of variability has been corrected for random errors by estimating instrumental noise in both cases using the procedure based on the regression of σ versus h_x described by Menenti and Ritchie (1994). The range shown is $2(\sigma\text{-}\sigma_0)$ where σ_0 is the y-intercept of the regression.

The unavailability of other pairs of field and laser measurements as precisely co-located as the ones presented above is unfortunate since, as clearly shown by the data plotted in figure 3 where the laser did not hit vegetation elements at heights < 20 cm as frequently as the probes used in the field measurements. When averaging all three horizontal resolutions for the field measurements of line 2, the results are:

$$\text{Laser} \qquad \bar{h}_x = 26{\cdot}1 \pm 17{\cdot}6\,(\text{cm})$$

$$\text{Field (average)} \qquad \bar{h}_x = 21{\cdot}5 \pm 16{\cdot}4\,(\text{cm})$$

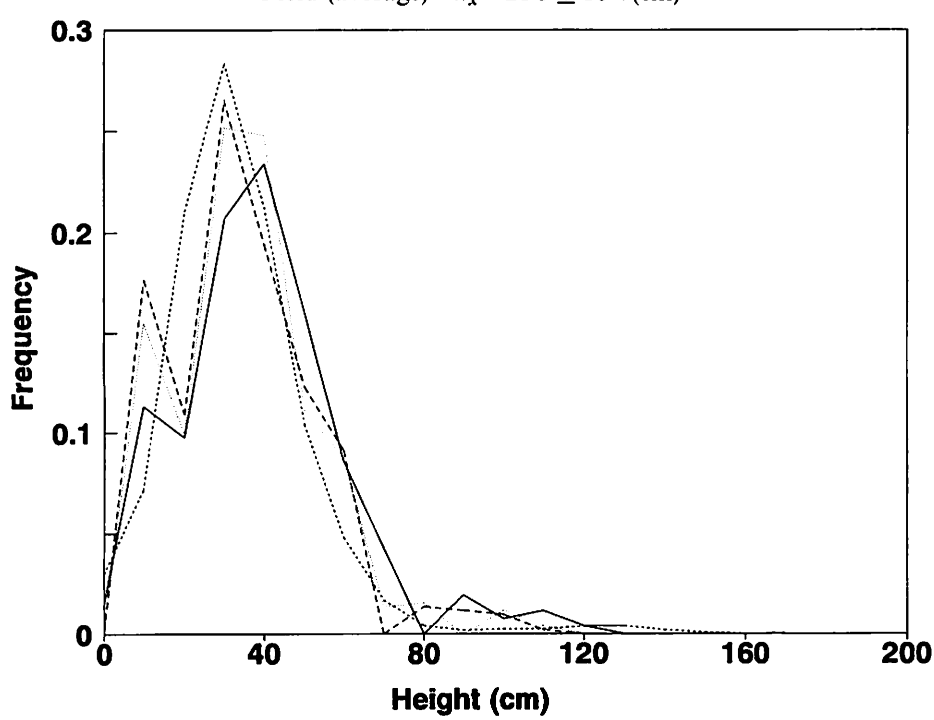

Figure 3. Frequency distribution of vegetation heights for site 2 line 1 obtained with laser (------ laser) and field measurements at different horizontal resolutions (——— 0·5 cm, ······ 1·0 cm, —— 2·0 cm). Co-location error of the field and laser measurements was less than 5 m.

Indication that the laser data represented spatial variability is provided by the data plotted in figure 4. Although the laser data did not correctly account for the smaller vegetation elements (i.e., $h_x < 20\,\mathrm{cm}$) measured in the field, the frequency distribution of laser and field measurements are similar. Again the inability to make field and laser measurements along the exact line (footprint) could account for most of the differences.

Differences in frequency distribution of field and laser measurements were evaluated by calculating the sum of the squared deviations for each set of field measurements and the average distribution of the laser measurements at sites 2 and 3. The 0·5 cm probe gave marginally better agreement with a mean square root error of 0·04 using break points of 10 cm to determine the frequency distribution.

Although the frequency distribution of the laser measurements matches the frequency distribution of the field measurements done with the 0·5 cm probe better, the comparison of mean vegetation height leads to a slightly different conclusion. Using the 2·0 cm field measurements at site 3 only, the results are:

Laser	$\bar{h}_x = 26{\cdot}1 \pm 17{\cdot}6\,(\mathrm{cm})$
Field (2·0 cm)	$\bar{h}_x = 24{\cdot}7 \pm 27{\cdot}6\,(\mathrm{cm})$ line 1
Field (2·0 cm)	$\bar{h}_x = 26{\cdot}8 \pm 22{\cdot}1\,(\mathrm{cm})$ line 2

By comparing the frequency distributions in figure 3 with the ones in figure 4 we see that the laser measurements give frequency distributions similar to the ones obtained with the laser measurements, and this statement applies to both line 1 and

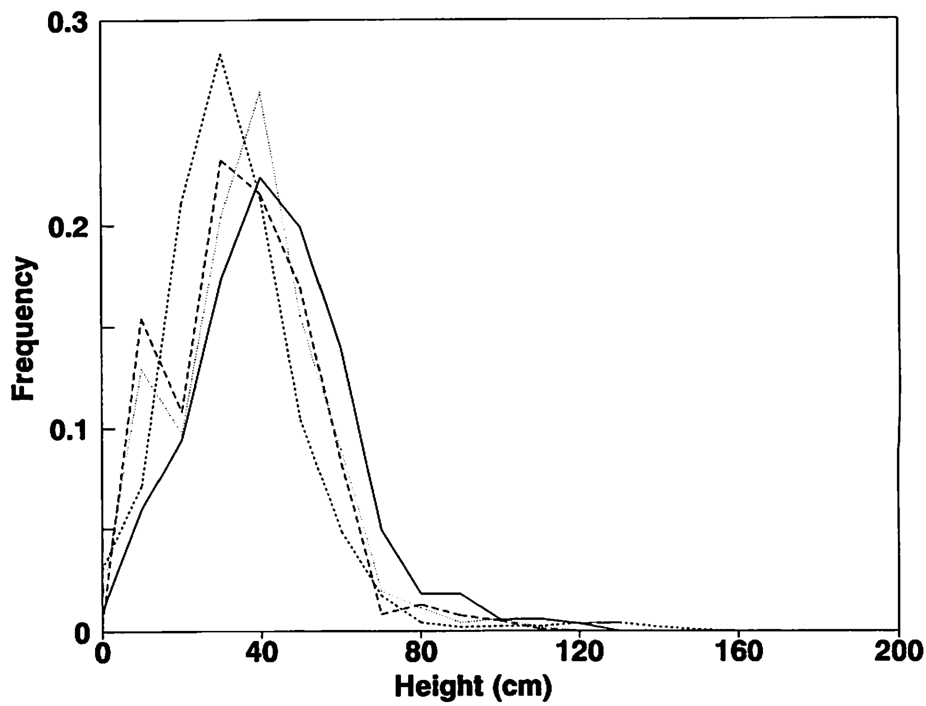

Figure 4. Frequency distribution of vegetation heights for site 2 line 1 and 2 obtained with laser (--- --- laser) and field measurements at different horizontal resolutions (——— 0·5 cm, ······ 1·0 cm, —— 2·0 cm). Observations at lines 1 and 2 have been merged.

2. To some extent the probe sizes can explain the differences. There is a small but a significant shift of observed frequencies towards greater vegetation height as probe size increases. A similar conclusion is reached when looking at mean vegetation height obtained with laser and ground measurements at site 3. Differences in mean vegetation height between ground and laser measurements are much smaller than the standard deviation for both lines 1 and 2. It may be concluded that precise co-location of laser and ground measurements is not critical to the outcome of this validation exercise.

The laser altimeter provides measurements of vegetation height as accurate as the detailed and time-consuming procedure applied in the field experiments. The similarity between the frequency distributions (figure 2–4) and the mean vegetation heights (tables 3–6) of field and laser measurements shows that the actual horizontal resolution of the laser is a fraction of the nominal footprint. Based on the similarity of the distribution of height values between field and laser measurements it is estimated that the actual laser footprint is between 0·5 and 2·0 cm and probably closer to the 2·0 cm. Calculations based on the power emitted by the laser transmitter and the power threshold needed to trigger the photodiode of the laser receiver (table 2) also show that backscatter from objects smaller than the nominal footprint size is sufficient to trigger the receiver. Assuming no atmospheric absorption or scattering, a target reflectivity of 1, and same divergence of the beam after reflection, a target as small as 0·24 cm in diameter would reflect enough light to trigger the receiver at 300 m. These conditions are never met in the field. It is difficult to calculate an actual footprint size since the reflectivity of the targets, atmospheric absorption and scattering conditions, and beam divergence of the reflected pulse all vary in time and space. However, field measurements indicate that objects smaller than the nominal footprint can be observed with the laser.

6. Measurements of land surface features with a laser altimeter

Detailed measurements of microtopography have been made by analysing laser data from ground level instruments (Huang and Bradford 1992). Similar measurements from approximately 2·1 s (8192 laser measurements) of laser altimeter data (Nig92-23), collected at an altitude of 225 m were used to generate a 160 m profile (figure 5) of the land surface in an agricultural field east of the town of Fandou Beri in the East Central super site (field measurement site 2). The raw airborne laser profile (figure 5) shows variations in the surface roughness superimposed on the overall topography. This profile also has the random and system noise signals associated with the laser system electronics. While determining the general shape and pattern of the macrotopography is possible, better data on land surface roughness features can be obtained when the random and system noise signals are reduced. The lower profile in figure 5 is derived from the upper profile using an 11-measurement moving average filter. The lower profile shows the same macrotopographic profile shape as the upper profile but now surface microtopography variations due to a combination of soil roughness and vegetation are seen. Many processes on and across the land surface boundary layer are controlled by surface microtopography or roughness. Soil and vegetation microroughness have been shown to influence seed germination, water retention, infiltration, evaporation, runoff and soil erosion by water and wind (Zobeck and Onstad 1987). Measurements of microroughness of the land surface will help explain, and more accurately estimate, evaporation, soil moisture, runoff and soil erosion at local and landscape scales.

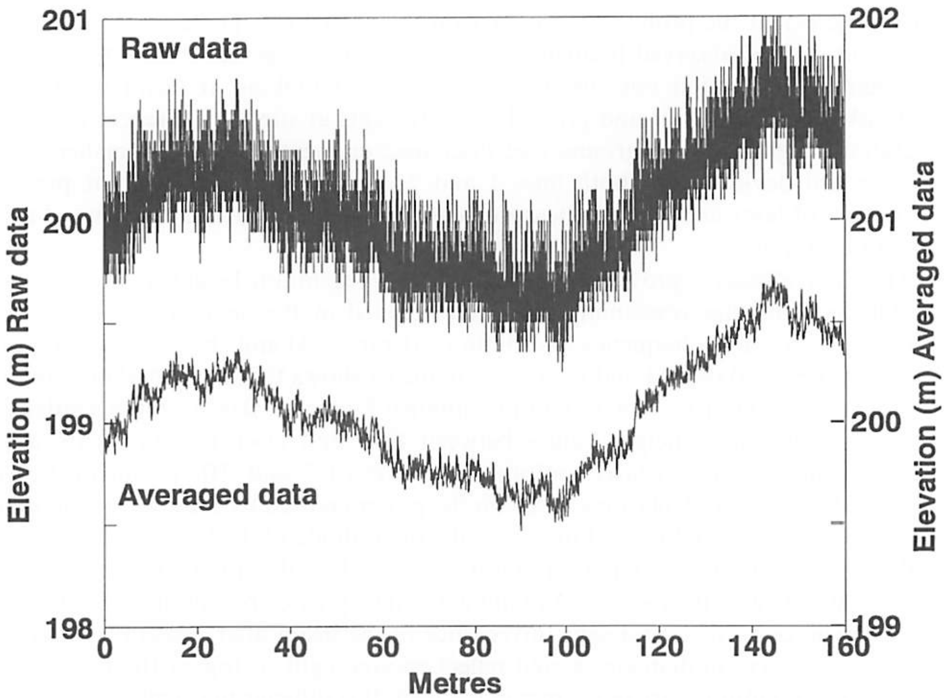

Figure 5. Landscape surface profile measured in an agricultural field in Niger, Africa. The upper profile is data as collected (raw data) and the lower profile is derived from the upper profile using a 11-measurement moving average.

Laser altimeter measurements provide data on land surface patterns related to microroughness for areas from less than a metre to kilometres. While there is need for data on microroughness at different scales of the land surface, there is also a need for data on macrotopographic changes over distances from metres to kilometres. An airborne laser altimeter can be used to measure topographic patterns for long profiles quickly and efficiently. At the C-130 ground speed of $75\,m\,s^{-1}$, a 4·5 km profile is measured each minute (240 000 laser measurements) with the same detail as shown for short profiles (figure 5).

A topographic profile (figure 6) from the valley bottom to the plateau north-east of the town of Banizoumbou in the East Central super site shows a longer laser profile. This profile is from laser data block-averaged using 25 laser measurements ('footprint' is approximately 60 cm). Block averaging was used in this example to be able to display the data effectively. This profile shows riparian vegetation in the valley bottom near a stream channel and vegetation on top of the plateau. The vegetation on the plateau shows the row pattern that is typical of the tiger bush community present on the plateau. Several erosional scars are evident on the slopes of the valley that support vegetation. There is approximately 40 m difference in elevation from the valley bottom to the plateau. These vertical land surface elements (topography and vegetation) would affect air movement and aerodynamic roughness of the region. Surface water flow and retention would be affected by erosion scars and by the vegetation growing in these scars on the slopes of the valley. Vegetation growing in the erosion scars would be related to amount of water retention.

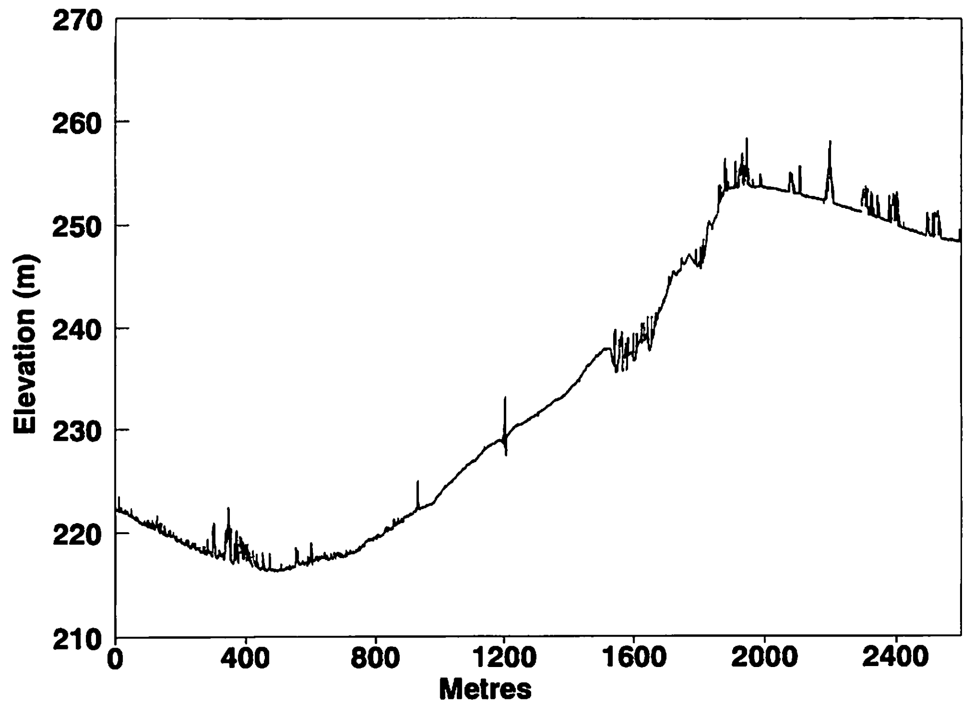

Figure 6. Topographic profile made using an airborne laser altimeter of a river valley in Niger, Africa. Profile was made by block averaging 25 laser measurements.

Soil erosion and stream channel degradation are major problems around the world. These features need to be measured to determine the extent of their damage to the land surface, to estimate their effects on soil loss in terms of productivity and water quality, and to estimate water flow across the landscape. Measurements of these features can be difficult and time-consuming using ground-based techniques. A stream valley cross-section (figure 7) east of Banizoumbou was measured with the laser altimeter data (Nig92–14). This 500 m cross-section was calculated using a block average of eight measurements. It shows the gentle slope on the outside of the channel and the steeper slope on the inside of the channel. Such measurements can allow a better understanding of water flow in the channel and water removal from the area.

Measurements of smaller erosional features on the land surface were also made with the airborne laser altimeter (figure 8). Three small gullies are shown in this topographic cross-section in an area north of Fandou Beri. If the original land surface can be represented using a straight line between the top edges of the gully, the cross-sectional areas of the three gullies were measured to be 10·03, 7·69 and 1·11 m^2 respectively. Other shaped lines (i.e., concave, convex) or placement of line for the original land surface could have been used. Using these techniques, cross-sections of larger gullies and stream channels have been measured (Ritchie *et al.* 1994). Such measurements can be used to measure gully and stream channel cross-sections, gully erosion, stream bank erosion, meandering, channel degradation, estimate soil loss and impacts on water quality problems, and measure channel roughness and cross-sections for estimating flow rates. Data on channel and gully size,

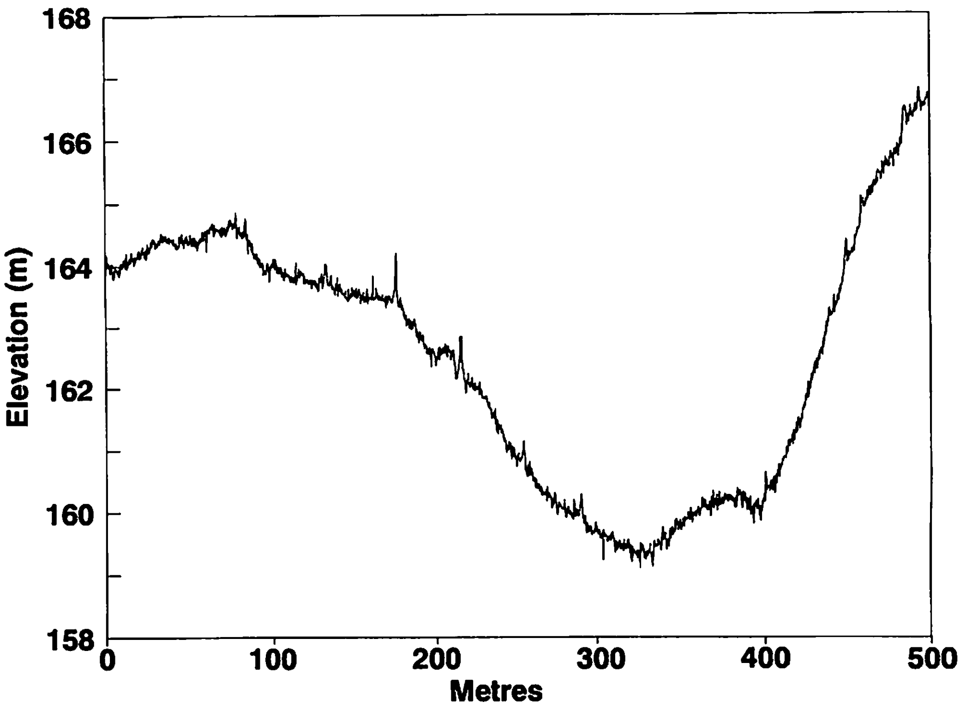

Figure 7. Laser altimeter measurements of a valley cross section east of Banizoumbou, Niger. Laser data were block averaged using eight measurements.

roughness, and degradation will help in design and development of physical and biological structures to control problems and flow.

These profiles show the types of microtopographic and macrotopographic data that can be collected with the laser altimeter. While the maximum length shown was 2·5 km, profiles could be measured and analysed for any length required. Greater spatial and vertical detail on these profiles could be measured by using smaller block averages or by using all the data points and a moving average filter. Topographic profiles can be collected easily and efficiently with an airborne laser altimeter and can be used to provide topographic profiles of the land surface. Ease and speed of data collection would allow measurement of multiple profiles with a minimum of extra survey cost. These measurements of topography provide data for understanding land degradation and water and wind flow across the landscape. Applications of these data for understanding water and heat budgets on the land surface are being studied (Menenti and Ritchie 1992, 1994, Ritchie *et al.* 1993 b). Understanding these budgets is important for understanding patterns of land surface change.

Vegetation properties on the landscape can also be measured using laser altimeter data. The ground surface under a vegetation canopy is estimated by assuming that minimum elevation measurements along transects represent laser measurements that penetrated the canopy and reached the ground surface. By calculating the difference between the estimated ground surface (minimum elevation measurements) and the actual laser measurements, canopy height, canopy cover and distribution can be calculated. Studies have shown that altimeter measurements provided accurate measurements of vegetation heights and cover (Ritchie *et al* 1992, Weltz *et al.* 1994).

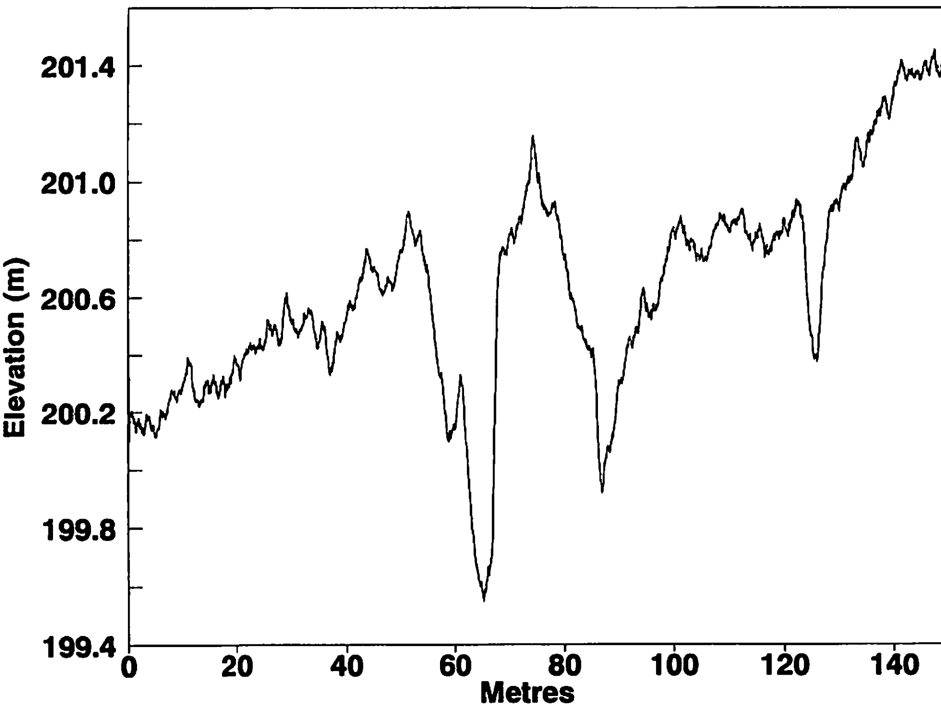

Figure 8. Topographic cross section over three small gullies in an eroded area north of Fandou Beri, Niger. Laser data were analysed using a block average of 8 measurements.

Vegetation heights along two profiles at a fallow site of the West Central super site are shown in figure 9. Fallow is defined as an abandoned agricultural area where shrubs dominate. Guiera (*Guiera senegalensis* L.) is the dominant shrub at these sites. These profiles are from two flight lines (Nig92-13 and Nig92-15) approximately 100 m apart and were analysed using 8 measurement block averages. The maximum height of the vegetation at these two sites was between 2 and 3 m that is similar to that reported by Wallace *et al.* (1993) for a similar vegetation at the Southern super site and by Bégué *et al.* (1994) for a site near Ouallam in north-western Niger. If measurements less than 0·5 m are eliminated, then average height of the upper canopy is $1{\cdot}34 \pm 0{\cdot}55$ m and $1{\cdot}42 \pm 0{\cdot}57$ m for fallow sites A and B, respectively, which is similar to data reported by Bégué *et al.* (1994) and Franklin *et al.* (1994).

Vegetation cover can also be estimated from this height data. Since the height data represent laser pulses reflected by vegetation along the line then any measurement greater than zero (>0) can be assumed to have been reflected by vegetation (or a man-made structure). Therefore, by determining the number of non-zero measurements and dividing that by the total number of laser pulses, an estimate of the vegetation cover was made. A frequency distribution of the height measurements (table 7) was used directly to estimate vegetation cover by height intervals. About 90 per cent of the measurements were less than 0·5 m showing that only about 10 per cent of this fallow area is covered with vegetation greater than 0·5 m tall. If only vegetation greater than 1 m is considered then cover is 6·3 and 7·4 per cent for fallow sites A and B, respectively, which is consistent with the estimate of 6 per cent for

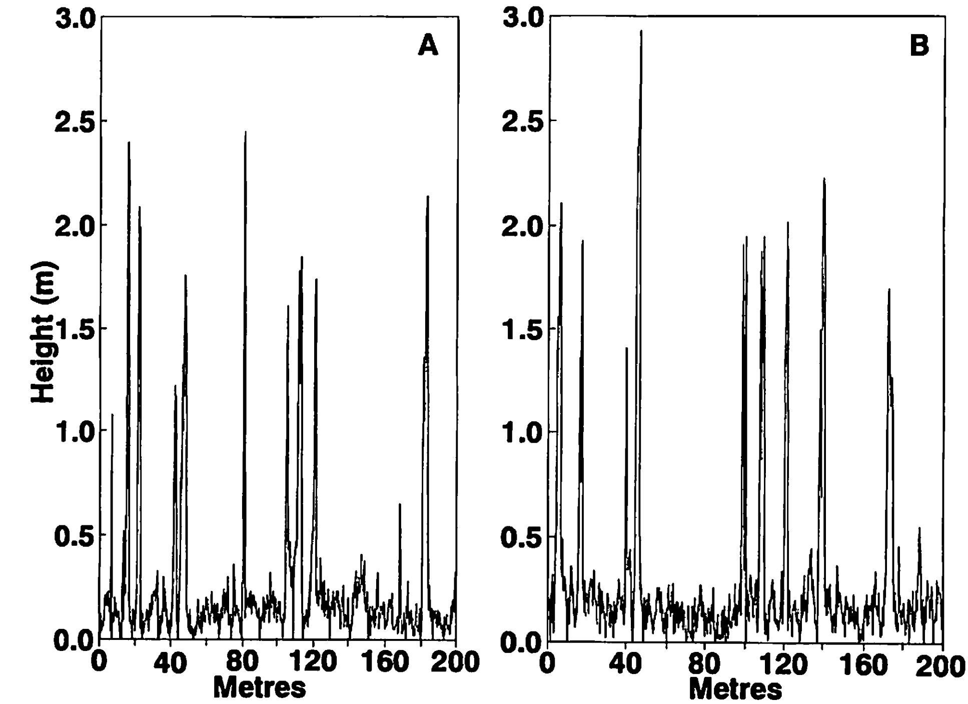

Figure 9. Vegetation heights along two transects at a fallow site (*Guiera senegalensis* L.) at the HAPEX-Sahel West Central super site calculated from the laser altimeter data using a block average of 8 measurements.

Table 7. Vegetation heights measured for two 200 m profiles of laser altimeter data at a fallow site in the West Central super site. Percentage distribution of laser measurements by height interval are given. Fallow sites A and B are shown in figure 6.

Height (m)	Fallow A %	Fallow A cumulative (%)	Fallow B %	Fallow B cumulative (%)
0·0–0·1	32·4	32·4	23·2	23·2
0·1–0·2	38·3	70·7	38·8	62·0
0·2–0·3	13·6	84·3	20·0	82·0
0·3–0·4	3·3	87·6	5·2	87·2
0·4–0·5	2·7	90·3	1·9	89·1
0·5–0·6	1·0	91·3	1·3	90·4
0·6–0·7	0·3	91·6	0·5	90·9
0·7–0·8	0·4	92·0	0·3	91·2
0·8–0·9	1·0	93·0	0·6	91·8
0·9–1·0	0·1	93·1	0·4	92·2
1·0–2·0	5·2	98·8	6·0	98·6
2·0–3·0	1·1	100·0	1·4	100·0

Guiera by Bégué *et al.* (1994). Franklin *et al* (1994) reported a 7 per cent cover for the shrub component (Guiera) in this vegetation type in the same area.

A similar vegetation height and cover analysis was done for longer segments of flight lines Nig92-13 (14 km) and Nig92-14 (18 km) over the West Central and East Central super sites. The frequency distribution (table 8) is similar to the fallow site

Table 8. Vegetation heights measured for 14 and 18 km profiles of laser altimeter data across the West Central and East Central super sites. Percentage distribution of laser measurements by height interval is given.

Height (m)	Nig92-13 %	Nig92-13 cumulative (%)	Nig92-14 %	Nig92-14 cumulative (%)
0·0–0·1	31·8	31·8	29·8	29·8
0·1–0·2	38·2	70·0	41·6	71·4
0·2–0·3	16·3	86·3	16·1	87·5
0·3–0·4	6·0	92·3	5·2	92·7
0·4–0·5	2·5	94·8	2·2	94·9
0·5–0·6	1·1	95·9	1·1	96·0
0·6–0·7	0·6	96·5	0·7	96·7
0·7–0·8	0·4	96·9	0·4	97·1
0·8–0·9	0·4	97·3	0·3	97·4
0·9–1·0	0·3	97·6	0·3	97·7
1·0–2·0	1·5	99·1	1·8	99·5
2·0–3·0	0·4	99·5	0·2	99·7
>3·0	0·5	100·0	0·3	100·0

but with only 5 per cent of the vegetation being greater than 0·5 m tall. As with the fallow, there was a significant increase in frequencies between 1·0 and 2·0 m tall. If we assume that the height measurements between 1·0 and 2·0 m tall represent the fallow type vegetation (Guiera), then between 1·5 to 1·8 per cent of the landscape has this taller fallow type vegetation. However, most of the land surface is covered with short vegetation. This short vegetation (<0·5 m) would influence the overall aerodynamic roughness, while the 2·4 per cent of the vegetation that is greater than 1·0 m tall might affect local turbulence and evaporation in the downwind direction depending on its spatial distribution. More detailed studies of these longer profiles need to be made to determine if the spatial patterns of distribution of this taller vegetation are random or if they are related to predictable landscape features (i.e., riparian vegetation, low area).

Another significant natural vegetation type is the tiger bush community that occurs on the plateaus. The tiger bush community is dominated by 2–4 m shrubs (*Combretum micranthum* G. Don and *Guiera senegalensis* L) and 4–8 m trees (*Combretum nigricans* Lepr ex Guill. and Perrott.) and a variety of less abundant shrubs and herbs (Wallace *et al.* 1993). This vegetation type was not sampled on either of the long flight line segments already discussed. Two 1000 m transects of vegetation heights of a tiger bush community on the plateau south of Fandou Beri near a Dutch meteorological study site are shown in figure 10. These transects were taken from two different flight lines (Nig92-24 and Nig92-25), one north of the meteorological tower and one south of the tower.

The row pattern of the vegetation is evident. If measurements less than 0·5 m are eliminated then the average heights of the vegetation are 2·10 ± 0·92 and 2·17 ± 1·04 m respectively for tiger bush A and tiger bush B. There are 10 rows of tiger bush in each transect showing an average distance of 100 m between the centre of rows. A third 1000 m transect of tiger bush from the community on the plateau north-east of Banizoumbou shown in figure 6 had an average height of 2·20 m and an average distance between rows of 100 m. These measurements are consistent with those reported for the Southern super site (Wallace *et al.* 1993) where the tiger bush was

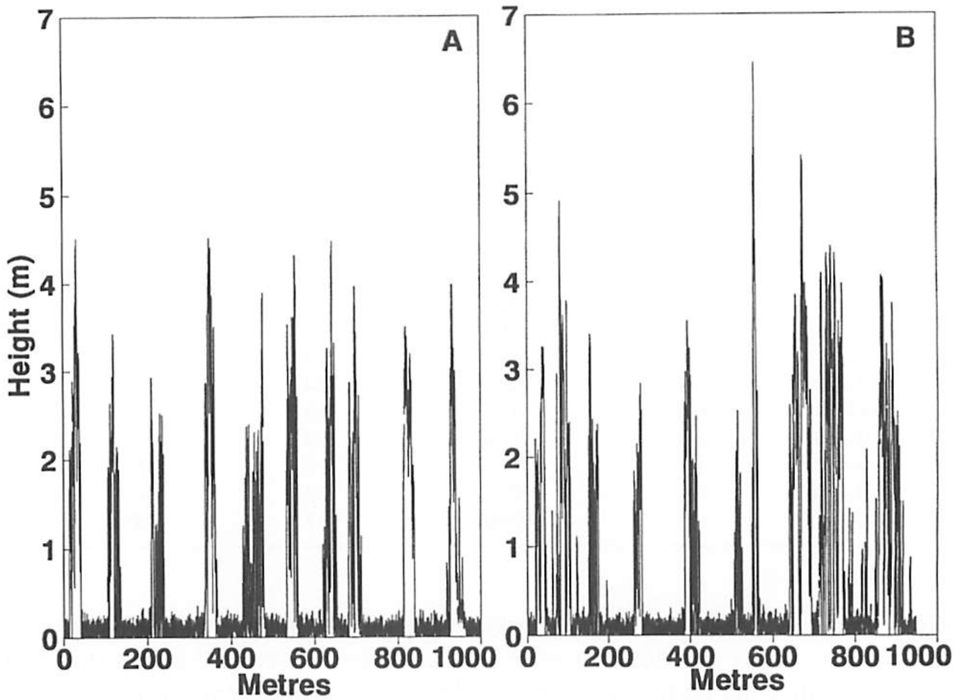

Figure 10. Vegetation heights measured over two flight lines in a tiger bush community on the plateau south of Fandou Beri, Niger. Laser data analysed using a block average of eight measurements.

10–30 m wide by 100–300 m strips. Widths for the tiger bush rows measured with the laser data were between 20 and 40 m.

The frequency distribution of vegetation heights at the tiger bush site (table 9) shows a much higher per centage (22·5 and 30·1 per cent for sites A and B respectively) of vegetation cover greater than 0·5 m tall than at the fallow sites or the long transects. There were also a significant number of measurements of vegetation between 1·0 and 4·0 m tall. Culf *et al.* (1993) reported cover of 33 per cent for a tiger bush community at the Southern super site. White (1970) found cover of 21 to 31·5 per cent for tiger bush communities in the 400 to 750 mm rainfall areas.

7. Conclusions

Topographic differences and vegetation patterns are integral parts of the landscape. To understand land degradation and hydrological and biological systems on natural and agricultural landscapes at large length scales, these properties have to be measured and evaluated quantitatively. An airborne laser altimeter can be used to measure landscape topography, gully and stream cross-sections and vegetation canopy properties. The comparison of field and laser measurements indicates that objects smaller than the nominal footprint can be observed with the laser. The agreement of laser data with field measurements was good for vegetation height and frequency distribution of height. Laser measurements of microtopography and macrotopography can contribute to quantification of water retention, infiltration, evaporation, and movement from land surfaces and in channels and across the land surface. Channel and gully development and degradation was measured and can be

Table 9. Vegetation heights measured for two 1000 m profiles of laser altimeter data at a tiger bush site on a plateau south of the town of Fandou Beri. Percentage distribution of laser measurements by height interval is given. Tiger bush sites A and B are shown in figure 10.

Height (m)	Tiger bush A %	Tiger bush A cumulative (%)	Tiger bush B %	Tiger bush B cumulative (%)
0·0–0·1	39·4	39·4	36·9	36·9
0·1–0·2	29·7	69·1	25·4	62·3
0·2–0·3	6·0	75·1	4·7	67·0
0·3–0·4	1·5	76·6	1·8	68·8
0·4–0·5	0·9	77·5	1·1	69·9
0·5–0·6	0·8	78·3	1·1	71·0
0·6–0·7	0·8	79·1	0·8	71·8
0·7–0·8	0·6	79·7	0·9	72·7
0·8–0·9	0·7	80·4	0·8	73·5
0·9–1·0	0·6	81·0	0·7	74·2
1·0–2·0	8·9	89·1	10·9	85·1
2·0–3·0	7·8	96·9	9·3	94·4
3·0–4·0	2·6	99·5	4·4	98·8
4·0–5·0	0·5	100·0	0·8	99·6
5·0–6·0	0·0	100·0	0·4	100·0

used to estimate soil loss and explain water quality and flow patterns. Measurements of canopy properties and their distribution across the landscape and their effects on water movement and aerodynamic roughness allow better understanding of evaporative loss, infiltration and surface water movement. Airborne laser altimeters offer the potential to measure land surface features and properties over large areas quickly and easily. Such measurements will improve our understanding of the effect of these factors on land degradation, and the hydrological and biological systems on natural and agricultural landscapes.

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