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Airborne laser altimeter applications to water management

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Abstract Landscape shape and surface roughness are key properties for understanding factors related to the management of water and natural resources. These properties have to be measured and evaluated quantitatively at large scales to understand hydrologic systems on natural and agricultural landscapes. It is difficult and time consuming to measure roughness at scales that are large enough to be useful for understanding water movement on the landscape using current techniques. Airborne laser altimeter data can be used to measure topography, gully and stream cross sections, vegetation canopy, and other landscape roughness properties for large areas. The agreement between laser altimeter and field measurements is good for topographic features, vegetation properties (i.e. height, frequency distribution of height, and cover). Airborne laser measurements of micro and macro topography can be used to quantify water retention, infiltration, evaporation, and water movement across land surfaces and in channels. Channel and gully measurements can be used to estimate soil loss and explain water quality and flow patterns. Measurements of distribution of plant canopy properties 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 landscape roughness on hydrologic systems on natural and agricultural landscapes. Laser altimetry is an additional tool in the arsenal of remote sensing tools used to understand drainage basin properties and to develop plans to manage water resources.

INTRODUCTION

Data on complex patterns of surface roughness features on the landscape are needed to understand and manage hydrologic systems. Determining spatial patterns of topography and landscape features with conventional ground-based or aerial technologies are difficult, time consuming, and expensive. By adapting laser distancing technology to airborne platforms, rapid and accurate measurements of landscape surface shapes, features and patterns can be made. This paper discusses the application of airborne laser altimetry to measurements of features and patterns of landscape surfaces and discusses their potential applications for management of water resources for natural and agricultural ecosystems.

METHODS AND MATERIALS

The distance from an airplane to the landscape surface can be measured with a laser altimeter mounted in the airplane. Landscape surface elevation can be calculated for each laser measurement based on known ground elevations along a flight line or by using Global Positioning System (GPS) data. Minimum elevations measured along a flight line are assumed to be ground surface elevations with measurements above these minima due to vegetation or manmade structures.

The altimeter used in this study was a gallium-arsenide diode laser, transmitting and receiving 4000 pulses per second at a wavelength of 0.904 μm. With a field-of-view of 0.6 milliradians, the receiver sees a "footprint" on the ground that is approximately 0.06% of the altitude. The timing electronics of the laser receiver allow a vertical resolution of 5 cm for each measurement. Digital data (distance from the airplane to the landscape surface) from the laser receiver along with data from a gyroscope and an accelerometer mounted on the base of the laser platform were recorded with a portable personal computer. A video camera, borehole-sighted with the laser, recorded an image of the flight line. Sixty video frames were recorded per second. Frames are annotated with consecutive numbers, clock time, and GPS data. Video frame numbers were recorded with the digital laser data to allow precise location of the laser data on the landscape with the video data for these studies.

RESULTS AND DISCUSSION

Laser altimeter data, collected at an altitude of 225 m, were used to generate a 100-m profile of the surface of a bare agricultural field at the USDA Agriculture Research Service (ARS) Little Washita basin near Chickasha, Oklahoma USA (Fig. 1). The

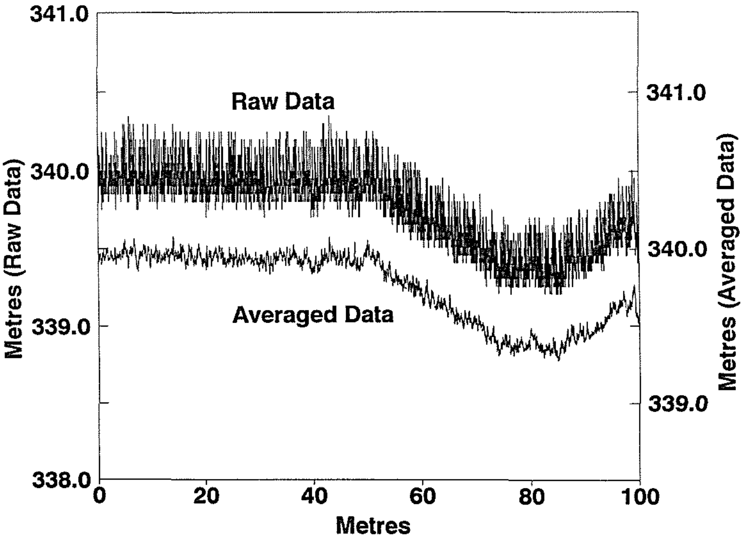

Fig. 1 Bare soil profile measured in an agricultural field in the Little Washita basin, Oklahoma. The lower profile was derived from the upper profile (raw data) using an 11-measurement moving average filter.

upper profile (Fig. 1) is laser data processed to show elevation of the landscape surface. This profile contains the laser return signals from the landscape surface as well as random and system noise signals associated with the laser system electronics. While the shape of the landscape is shown, better data on landscape surface features can be obtained by reducing the random and system noise using a moving average filter (McCuen & Snyder, 1986). The lower profile (Fig. 1), derived from the upper profile using a 11-measurement moving average filter, shows the same general topographic profile shape as the upper profile but with variations due to a combination of topography and soil roughness visible. If topography or oriented roughness (Allmaras *et al.*, 1966) is removed then soil surface roughness (Kuipers, 1957) or random roughness (Allmaras *et al.*, 1966) can be calculated. The average soil surface height and standard deviations are 14.7 ± 10.3 cm and 6.4 ± 3.6 cm for upper and lower profiles, respectively, after the topography (oriented roughness) was removed. Using Kuipers (1957) technique, soil surface roughness is calculated to be 101 and 55 for the upper and lower profiles, respectively. Such soil roughness measurements have been used to estimate water retention, infiltration rates, evaporation, runoff, seed germination, and soil erosion by water and wind (Zobeck & Onstad, 1987). Thus laser measurements (Fig. 1) of micro-roughness of the soil surface can be used to more accurately understand and predict evaporation, soil moisture, runoff, and soil erosion at landscape scales.

Larger scale roughness features can also be quantified to estimate their effects on soil loss, water quality, and water flow across the landscape. The channel and valley associated with Reynolds Creek near the outlet of Reynolds Creek basin near Boise, Idaho USA (Fig. 2) was measured using 2 s of airborne laser data. Actual laser altimeter data are shown. Mathematical filters were not used. The profile shows the channel cross section along with the valley associated with the channel. The channel cross section under the lower dashed line was calculated to be 48.94 m^2. Other stages

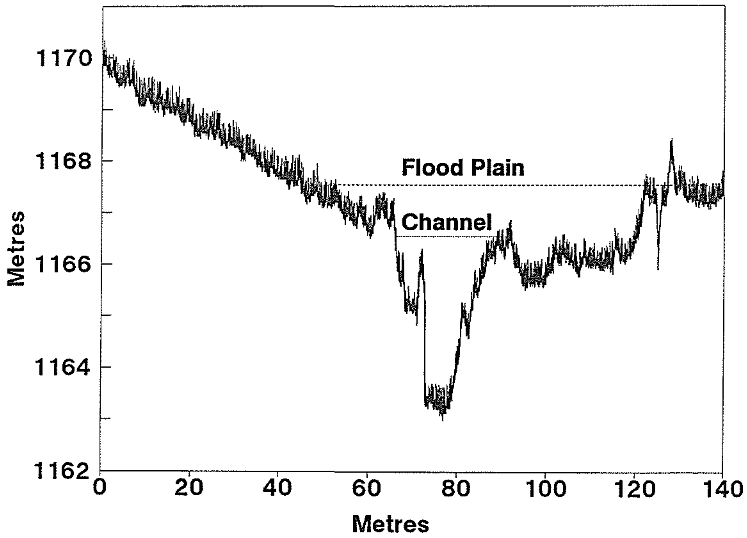

Fig. 2 Laser altimeter measured cross section of Reynolds Creek near Boise, Idaho. Dotted lines represent the top of the channel and the flood plain. The area of the channel under the lower dotted line is 48.94 m^2.

could be assumed (Fig. 2. upper dashed line) and their cross sections measured. Using such measurements of channel and flood plain cross sections and roughness would allow better estimates of channel and flood plain capacity and resistance to flow and potential flood area at different stages.

Using laser altimeter techniques, cross sections of gullies and stream channels have been measured at other sites (Ritchie *et al.*, 1993b; Ritchie & Jackson, 1989). Laser altimeter measurements were used to quantify gully and stream channel cross sections and roughness, gully erosion, stream bank erosion, channel degradation, and measure channel and flood plain roughness and cross sections for estimating flow rates. Data on channel, gully, and flood plain size, roughness, and degradation will provide valuable data for the design and development of physical structures to control flow, reduce bank erosion, and to calculate flows and areal extent of floods.

These examples show how laser altimeter measurements can provide data on landscape patterns related to roughness and geometry of soil surfaces, gullies, and channels and their associated landscape at small scales. While there is need for data on changes in micro roughness of landscape features, there is also need for data on topographic changes over distances from hundreds of metres to several kilometres. An airborne laser altimeter can be used to measure longer topographic profiles quickly and efficiently. At an airplane ground speed of 100 m s^{-1}, 6 km profiles are measured each minute (240 000 laser measurements) with the same detail as shown for short profiles (Fig. 1). An example of a topographic profile of a dune area at the ARS Jornada Experimental Range near Las Cruces, New Mexico, USA is shown in Fig. 3 using approximately 15 s of the laser altimeter data. Since the purpose was to measure macro topography rather than micro topography, block averaging 12 laser measurements was used to reduce the data, giving an effective laser measurement rate of 333 measurements per second resulting in a "footprint" length of 30 cm for this profile. The profile is from an area of dunes with mesquite shrubs on top of the

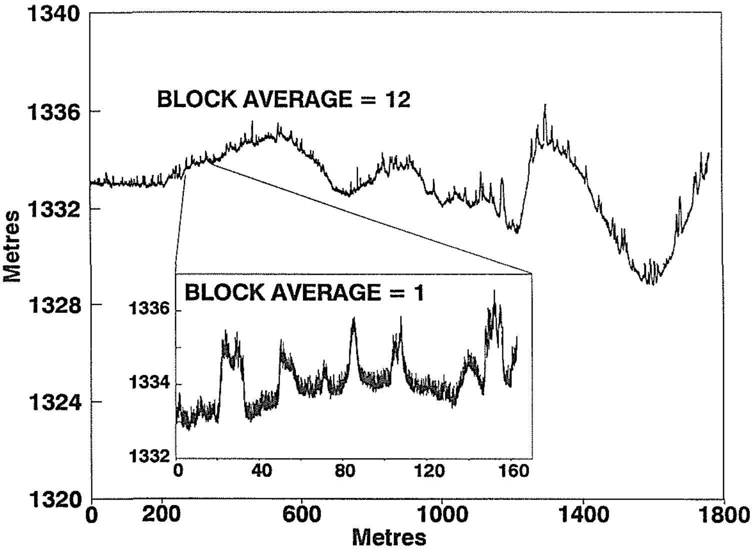

Fig. 3 Topographic profile measured using an airborne laser altimeter of dunes at Jornada Experimental Range near Las Cruces, New Mexico. The profile was made by block averaging 12 laser measurements.

dunes and almost no vegetation between the dunes. The insert in Fig. 3 shows the full resolution laser data of 1 to 3 m tall dunes and mesquite shrubs.

The profile shown in Fig. 3 illustrates the type of topographic data that can be collected with the laser altimeter. While the length of the profile shown was 1.8 km, profiles can be measured and analysed for any length. Greater spatial and vertical detail on such profiles can be measured by using smaller block averages or all data points (Fig. 3 Insert) with a filter. Ease and speed of data collection allow measurement of several profiles over the same area with a minimum of extra survey cost. Such measurements of topography provide data for estimating aerodynamic roughness and understanding water and wind flow across the landscape (Menenti & Ritchie, 1994; Menenti *et al.*, 1996).

Vegetation patterns associated with landscape roughness of a 100-m section of topographic profile from Reynolds Creek basin is shown in Fig. 4. Mathematical filters and block averages have not been used in the profile shown in Fig. 4. Landscape roughness and gaps between the larger vegetation elements are seen in Fig. 4(a). The ground surface under the vegetation is estimated assuming that minimum elevation measurements along the profile represent laser measurements that penetrated the vegetation and reached the ground surface. If the topography (oriented roughness) is removed by calculating the difference between the estimated ground surface and the actual laser measurements, vegetation heights and distribution can be measured (Fig. 4(b)). Earlier studies in Texas (Ritchie *et al.*, 1992), Mississippi (Ritchie *et al.*, 1993a) and Arizona (Weltz *et al.*, 1994) have shown that laser altimeter measurements provided accurate measurements of vegetation heights and cover that were highly correlated with ground measurements made using standard line transect techniques.

These measurements can be converted directly to estimates of vegetation canopy cover (Fig. 5) since any measurement greater that 0 ± 0.1 m can be assumed to be

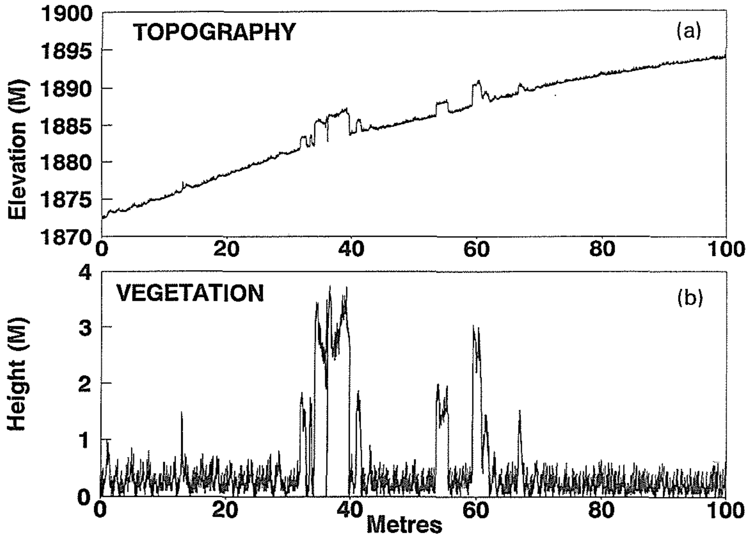

Fig. 4 Distribution (%) of vegetation heights calculated from data in Fig. 4(b). Heights intervals are 0.1 m. Total number of samples is 4763.

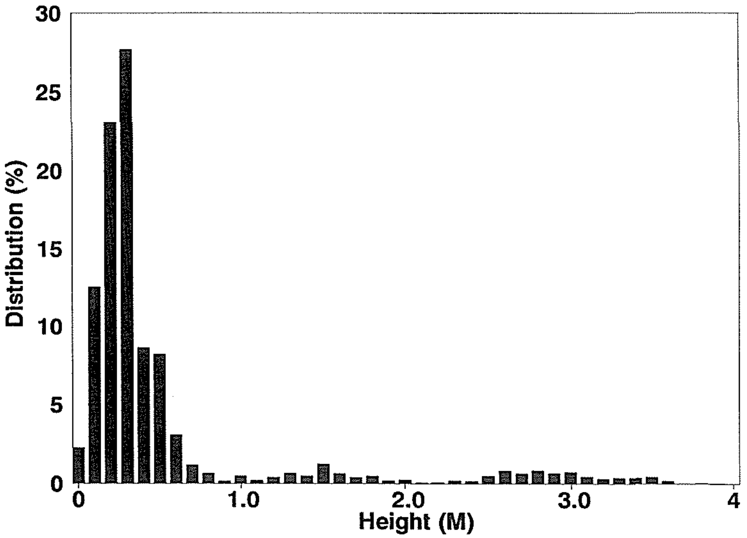

Fig. 5 Detailed measurements of landscape surface features (a) and vegetation heights (b) for a 100 m section from Reynolds Creek basin, Idaho. Filters were not used on the laser altimeter data.

reflected by a canopy element. Most of the canopy heights (74.2%) in this profile are less than 0.5 m tall. Only 12.5% of the height measurements are greater than 1 m. Using all data, the average canopy height for this segment is calculated to be 0.47 ± 0.73 m. Using only measurements greater than 0.5 m, the average canopy height is 1.77 ± 0.99 m.

Large scale measurements of canopy properties such as these shown for Reynolds Creek drainage basins will allow the separation of roughness due to physical and biological systems thus improving our understanding of spatial variability of landscape features and the functions that can be inferred from these features. Such data can help us understand infiltration, aerodynamic roughness (Menenti *et al.*, 1996; Menenti & Ritchie, 1994), evapotranspiration, phytomass, erosion, and other properties that will improve our understanding of the effect of these factors on the hydrology of natural and agricultural landscapes.

CONCLUSIONS

Airborne laser altimetry can provide rapid quantification of landscape topography, gully and stream cross sections and roughness and vegetation canopy properties for large areas. Land surface roughness due to the physical and biological properties and features can be separated and quantified. These properties and features are integral parts of the landscape and have to be evaluated at large scales to understand the hydrology of natural and agricultural systems. Measurements of these micro and macro surface features contribute to quantification of water retention, infiltration, evaporation, and movement from landscape surfaces and in channels and across flood plains. Channel and gully development, degradation, and roughness can be measured

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