Airborne Laser Altimeter Measurements of Landscape Topography

*Jerry C. Ritchie**

Measurements of topography can provide a wealth of information on landscape properties for managing hydrologic and geologic systems and conserving natural and agricultural resources. This article discusses the application of an airborne laser altimeter to measure topography and other landscape surface properties. The airborne laser altimeter makes 4000 measurements per second with a vertical recording resolution of 5 cm. Data are collected digitally with a personal computer. A video camera, borehole sighted with the laser, records an image for locating flight lines. GPS data are used to locate flight line positions on the landscape. Laser data were used to measure vegetation canopy topography, height, cover, and distribution and to measure microtopography of the land surface and gullies with depths of 15–20 cm. Macrotopography of landscape profiles for segments up to 4 km were in agreement with available topographic maps but provided more detail. Larger gullies with and without vegetation, and stream channel cross sections and their associated floodplains have also been measured and reported in other publications. Landscape segments for any length could be measured for either micro- or macrotopography. Airborne laser altimeter measurements of landscape profiles can provide detailed information on landscape properties or specific needs that will allow better decisions on the design and location of structures (i.e., roads, pipe, and power lines) and for improving the management and conservation of natural and agricultural landscapes.

INTRODUCTION

Complex landscape patterns with varying topography and surface properties (i.e., vegetation, roughness) influence the function and management of natural and agricultural resources and the location, design, and construction of structures and features to be placed on the landscape. Landscape patterns must be measured to improve management of natural and agricultural resources. While topography is routinely measured using ground techniques, aerial photography or satellite imagery, determining the spatial patterns with these conventional technologies can be difficult, time-consuming, often expensive, and usually limited to small areas.

Laser technology is used routinely to measure distances along survey lines on the ground. Adapting this technology to aerial surveys provides rapid and accurate assessment of landscape surfaces (Jepsky, 1986). Airborne laser altimeters have been used for mapping sea ice roughness (Ketchum, 1971), topography (Krabill et al., 1984), vegetation properties (Schreier et al., 1985; Nelson et al., 1988; Ritchie et al., 1992, 1993a), water depths (Penny et al., 1989), and gullies (Ritchie and Jackson, 1989; Ritchie et al., 1993b). Satellite-borne laser altimeters have also been used to investigate surface features of Earth and other planets (Bufton, 1989; Seshamani, 1993). This article discusses the application of airborne laser altimeter data for making detailed measurements of properties and patterns of the landscape surface for general or site-specific areas and needs and their applications to understanding and improving the management of natural and agricultural resources.

METHODS AND MATERIALS

An airborne laser altimeter was used to measure the distance from the airplane to the landscape surface. The landscape surface is defined by any object (i.e., soil, rock, vegetation, man-made structure) that reflects the laser pulse (Ritchie and Jackson, 1989). The altimeter is a pulsed gallium-arsenide diode laser, transmitting and receiving 4000 pulses per second at a wavelength of 904 nm. Power constraints limit the altitude (distance that can be measured) of the airplane to approximately

*Hydrology Laboratory, USDA ARS, Beltsville, Maryland

Address correspondence to Jerry C. Ritchie, Hydrology Lab., USDA ARS Beltsville Agriculture Research Ctr., BARC-West, Bldg. 007, Beltsville, MD 20705.

Received 6 April 1994; revised 7 January 1995.

REMOTE SENS. ENVIRON. 53:91–96 (1995)

655 Avenue of the Americas, New York, NY 10010

0034-4257 / 95 / $9.50
SSDI 0034-4257(95)00043-Z

300 m. Ground speed during the flights varied between 50 m / s and 100 m / s. Under these operating conditions, a laser measurement occurred at horizontal intervals of 1.25–2.5 cm along the flight line depending on the airplane ground speed. The field-of-view of the laser is 0.6 mrad, resulting in a "footprint" on the ground that is approximately 0.06% of the altitude. Therefore, at 100 m altitude the "footprint" is 6 cm. The timing mechanism of the laser receiver allows a vertical recording resolution of 5 cm for a single measurement. Under controlled laboratory conditions, the standard deviation of laser measurement of a stationary object is between 10 cm and 11 cm and is constant for distances between 50 m and 300 m. Signals due to random and system noise associated with the system electronics contribute to the standard deviation measured under field or controlled laboratory conditions. Mathematical filters were used to reduce the random and system noise signals and enhance the systematic variation in the laser data (McCuen and Snyder, 1986).

Digital data (distance from the airplane to the landscape surface) from the laser receiver are recorded with a portable personal 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 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, and each frame is annotated with consecutive numbers, clock time, and GPS (Global Positioning Satellite) data. Each video frame number is also recorded with the digital laser data by the computer to allow precise location of the laser data on the landscape with the video data. The GPS system data can also be collected digitally for use in locating flight lines.

Landscape surface elevation was calculated for each laser measurement based on known elevations along the flight line. The minimum elevations (maximum laser measurements between airplane and the landscape) along a laser flight line are assumed to be ground surface elevation with measurements above these minimums being due to vegetation or man-made structures. In areas of vegetation, the minimum elevation values (ground surface) can be estimated by calculating a moving minimum elevation over a preselected number of laser measurements. The number of laser measurements used to determine the minimum values will depend on the type and density of vegetation. Some manual editing of these automatically determined minimum elevations is required in areas of dense vegetation cover.

RESULTS AND DISCUSSION

Measurements of landscape surface were made over four study areas with different topographic features and properties (i.e., vegetation covers and densities, surface roughness) using the airborne laser altimeter. Examples of different types of landscape surface measurements will be used to demonstrate the information that can be collected and extracted from the laser altimeter data.

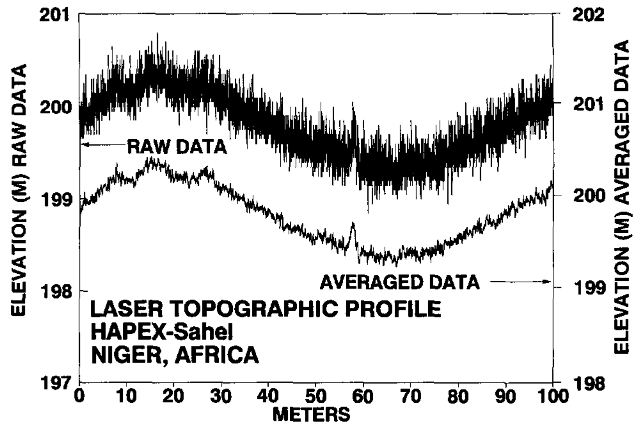


Figure 1. Landscape surface profile measured in an agricultural field in Niger, Africa. The upper profile was data as collected (raw data), and the lower profile was derived from the upper profile using an 11-measurement moving average filter.

Detailed measurements of microtopography can be made by analyzing laser data. Approximately 1.3 s (5134 laser measurements) of laser altimeter data, collected at an altitude of 200 m, was used to generate a 100-m profile of the landscape surface in an agricultural field in Niger, Africa (Fig. 1). This profile was collected in September 1992 during the 1992 HAPEX-Sahel experiment intensive study period. The upper profile in Figure 1 shows the "raw" laser data corrected to show surface elevations. While it is possible to determine the shape of the landscape, better information can be obtained if the random and system noise signals are minimized. A simple and effective method to reduce random and system noise signals and enhance systematic variations due to landscape features reflecting the laser pulse is to use a moving average filter (McCuen and Snyder, 1986). The lower profile in Figure 1 is derived from the upper profile using an 11-measurement moving average filter. The lower profile shows the same profile shape as the upper profile, but now variations due to a combination of soil roughness and vegetation can be seen. Such soil and vegetation roughness influence infiltration and soil erosion by water and wind. These measurements of the microroughness of the landscape surface can be used to more accurately predict soil moisture, runoff, and soil erosion at a landscape scale.

Soil erosion and stream channel degradation are major problems around the world. These erosional features need to be measured to determine the extent of their damage to the landscape and to estimate their

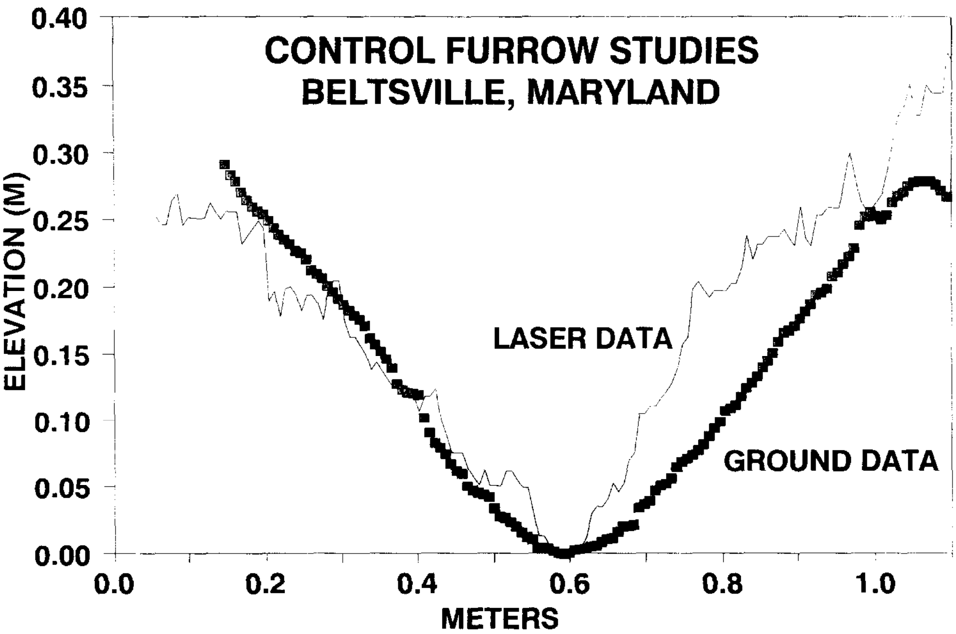
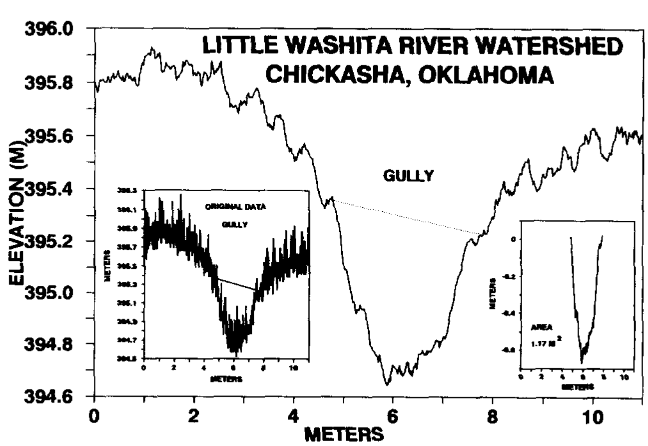


Figure 2. Comparison of ground and airborne laser measurements of a small furrow in a fallow agricultural field. Ground measurements made with a grid board. Laser measurements derived using a 21-measurement moving average.

effects on soil loss in terms of productivity and the offsite effects on water quality. Measurements of these features can be difficult and time-consuming using ground-based techniques. Laser altimeter measurements of a small furrow (gully) was verified under controlled conditions. The furrow in a fallow field at Beltsville, Maryland was measured with the airborne laser and also with a grid board (10 cm grids) placed in the furrow. The ground measurements were compared with airborne laser measurements of the same furrow (Fig. 2). The laser data were analyzed using a 21-measurement moving average filter. The comparison shows that the laser altimeter can be used to accurately locate and measure gullies as small as 20–30 cm wide and 15–20 cm deep from an altitude of 200 m.

Measurement of natural erosional features on the landscape were also made with the airborne laser altimeter (Fig. 3). The figure shows approximately 0.25 s of laser data taken from 180 m altitude over a pasture on the Little Washita River Watershed near Chickasha, Oklahoma. The original laser data (lower left insert, Fig. 3) shows the presence of a gully. Using an 11-measurement moving average filter, the shape and microroughness within the gully can be measured. By assuming that the original land surface can be represented using a straight line (dotted line, Fig. 3) between the edges of the gully, the cross-sectional area of the gully can be measured (lower right insert, Fig. 3) to be 1.17 m^2. Other shaped lines could have been used to represent the original land surface, but the principle for determining the cross section and area of a gully or stream channel is the same. Using these techniques, cross sections of larger gullies and stream channels have been measured (Ritchie et al., 1993b). Such measurements can be used to monitor gully development, stream bank erosion and meandering, channel degradation, estimate soil loss, water quality problems, and measure channel roughness and cross sections for estimating flow rates and problems. Data on channel and gully size, roughness, and degradation will assist in design and development of structures to manage these problems.

Figure 3. Laser altimeter measurements of a small gully on the Little Washita River Watershed, Oklahoma. The original data (insert lower left) were analyzed using an 11-measurement moving average filter. Insert lower right is area of gully.



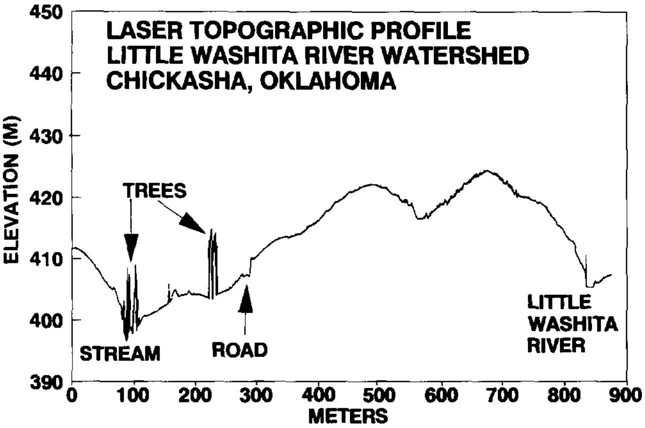


Figure 4. Topographic profile measured using an airborne laser altimeter in the Little River Watershed, Oklahoma. Profile was made by block averaging eight laser measurements.

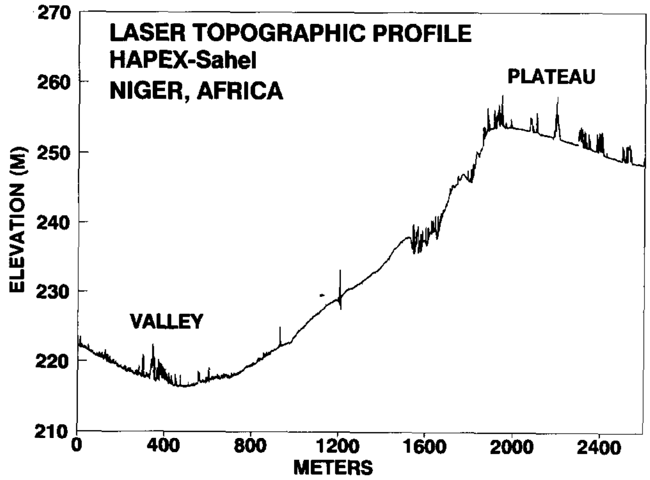


Figure 5. Topographic profile measured using an airborne laser altimeter of a river valley in Niger, Africa. Profile was made by block averaging 25 laser measurements.

Laser altimeter measurements can provide data on landscape patterns related to microroughness, gullies, and channels from less than a meter to several meters. While there is need for data on small changes and microroughness of the landscape, there is also need for data on large topographic changes over distances from hundreds of meters to several kilometers. An airborne laser altimeter can be used to measure topography over long segments quickly and efficiently. At an airplane ground speed of 50 m / s (the slowest speed used in these studies), 3-km profiles can be measured each minute (240,000 laser measurements). Three topographic profiles collected over different terrains and land covers will be used to illustrate the use of the laser altimeter for measuring long topographic profiles.

The first profile (Fig. 4) was measured in the Little Washita River Watershed near Chickasha, Oklahoma in June 1992. Since the interest was on macrotopography rather than microtopography, the amount of data used was reduced by block averaging eight laser measurements to give an effective laser measurement rate of 500 measurements per second. The profile is for an area between the Little Washita River and another small stream. The profile crossed a pasture / grass area between the streams. There are some trees (riparian vegetation) at the small stream and other trees about 100 m away. The flat surface in the Little Washita River indicates the presence of water since the infrared laser pulse does not penetrate water. There is only a 20-m difference in elevation along this 900-m profile, but the presence of the two valleys associated with the streams and the ridge between the streams can easily be measured.

The next profile (Fig. 5) is from the valley bottom to the plateau in a semiarid region of Niger in the Sudano-Sahelian zone of West Africa. This profile is from laser data that has been block averaged using 25 laser measurements. This profile again shows riparian vegetation in the valley bottom near a stream channel and vegetation on top of the plateau. The vegetation on the plateau shows a striped pattern that is typical of the "tiger" bush vegetation present on the plateau. There are also several erosional scars on the slope of the valley that support brush vegetation. There is approximately a 50-m difference in elevation from the valley bottom to the plateau.

The final profiles (Fig. 6) were measured for two flight lines along approximately the same flight line in the Walnut Gulch Watershed near Tombstone, Arizona. The laser data for these profiles were reduced by block averaging 30 laser measurements. These profiles cross rolling topography. There was only small shrub vegetation (<1 m tall) along these flight lines, so that no vegetation is evident in these 4-km profiles, where the elevation scale on the figure is 200 m. Studies on shorter lengths of these profiles showed the vegetation as low and small patches on the profiles (Ritchie and Weltz, 1992; Weltz et al., 1994).

These profiles show the type of topographic data that can be collected with the laser altimeter. While the maximum length profile shown was 4 km, profiles could be measured and analyzed for any resolution or length that was required. Topographic profiles can be collected easily and efficiently with an airborne laser altimeter and can be used to provide topographic profiles of the landscape necessary for many planning and design purposes such as roads, pipe lines, power lines, and diversion structures. Ease of data collection would allow design and planning for several profiles with a minimum of extra survey cost. Other applications including understanding water movement on the landscape surface from watersheds are being studied (Ritchie et al., 1993b; Menenti and Ritchie, 1992; 1994).

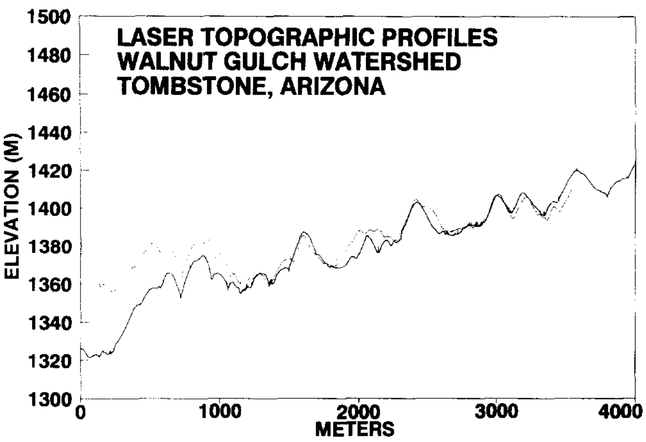


Figure 6. Two topographic profiles of the same general area measured using an airborne laser altimeter in the Walnut Gulch Watershed, Arizona. Profile was made by block averaging 30 laser measurements.

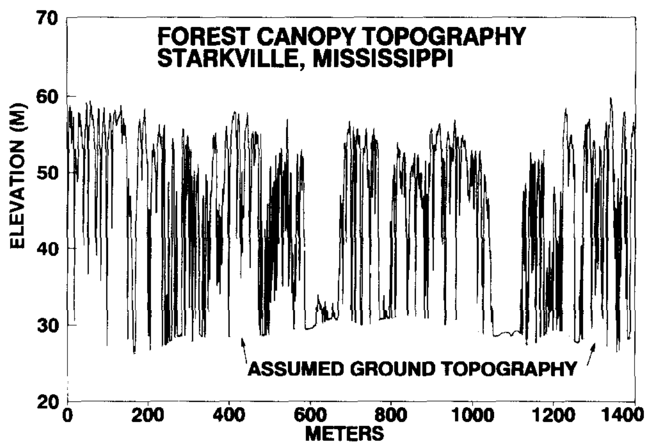


Figure 7. Airborne laser measurements of a forest canopy topography showing the ground topography (...) assuming the minimum laser measurements represent pulses reaching the ground through the canopy.

Properties of the vegetation on the landscape can also be measured using laser altimeter data. The topography of a mature pine (*Pinus* spp.) forest canopy near Starkville, Mississippi is shown in Figure 7. The pattern of the top of the canopy can be seen. The ground surface can also be seen and is estimated with the dotted line (Fig. 7) assuming that minimum elevation measurements along the transect represent laser measurements that penetrated the canopy and reached the ground surface. Using laser profiles of other parts of this forest, canopy height, cover, and distribution were determined (Ritchie et al., 1993a). Other studies of shrub and rangeland vegetation in Arizona and Texas showed that laser measurements of canopy height and cover were significantly correlated ($R^2 > 0.90$) with ground measurements made using line transect or line intercept methods (Ritchie et al., 1992; Ritchie and Weltz, 1992; Weltz et al., 1994). Other studies have shown that effective aerodynamic roughness can be estimated using the laser profile data (Menenti and Ritchie, 1992; 1994). Large scale measurements of canopy properties will provide better understanding of landscape functions and provide information that can be used to estimate erosion, infiltration, evapotranspiration, plant biomass, and other properties that will allow management plans to be made to conserve and improve the productivity of the natural and agricultural landscapes.

CONCLUSIONS

Micro- and macrotopography, erosion and drainage features, and ground cover are integral parts of the landscape. To better understand and manage natural and agricultural resources on a large scale, these properties have to be measured and evaluated. Measurements of the vertical surface properties of landscapes have been made using an airborne laser altimeter. Several applications of the airborne laser altimeter are presented in this article. The measurements have been used to quantify landscape topography, gully and stream cross sections, and vegetation canopy. Measurements of micro- and macrotopography contribute to better quantification of the movement of water over landscape surfaces and in channels and across flood plains. Channel and gully development and degradation can be measured and used to estimate soil loss and explain water quality and flow patterns. Measurements of canopy properties and their distribution across the landscape and their effect 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 landscape properties over large areas quickly and easily. Such measurements provide valuable data for understanding and managing natural and agricultural resources on a large scale and for designing, planning, and constructing structures on the landscape.

The author expresses appreciation to the USDA-ARS Remote Sensing Research Unit, Subtropical Agricultural Research Laboratory, Weslaco, Texas for the use of their Aerocommander and to the NASA Ames Research Center for the use of the NASA C-130 as platforms for flying the laser altimeter. Special appreciation goes to M. R. Davis, pilot, ARS, Weslaco, Texas, who flew the Aerocommander, R. E. Erickson, NASA coordinator of the C-130 activity, and Robert Parry, Hydrology Laboratory, Beltsville, Maryland, who operated the laser altimeter during several of the flights. Sincere appreciation is due to the staffs of the USDA-ARS Hydrology Laboratory, Beltsville, Maryland, USDA-ARS Remote Sensing Research Unit, Subtropical Agricultural Research Laboratory, Weslaco, Texas, USDA-ARS National Sedimentation Laboratory, Oxford, Mississippi, USDA-ARS National Agricultural Water Quality Laboratory, Chickasha and Durant, Oklahoma, USDA-ARS Southwest Watershed Research Center, Tucson, Arizona and the USDA Forest Service, *Southern Forest Experiment Station, Forest Inventory and Analysis Unit, Starkville, Mississippi, who provided logistical and ground support during the studies.*

REFERENCES

Bufton, J. L. (1989), Laser altimeter measurements from aircraft and spacecraft, *Proc. IEEE* 77:463–477.

Jepsky, J. (1986), Airborne laser profiling and mapping systems come of age, in *Technical Papers of the 1986 ACSM–ASPRS Annual Convention*, Vol. 4, American Society of Photogrammetry and Remote Sensing, Bethesda, MD, pp. 229–238.

Ketchum, R. D., Jr. (1971), Airborne laser profiling of the Artic pack ice, *Remote Sens. Environ.* 2:41–52.

Krabill, W. B., Collins, J. G., Link, L. E., Swift, R. N., and Butler, M. L. (1984), Airborne laser topographic mapping results, *Photogramm. Eng. Remote Sens.* 50:685–694.

Nelson, R., Krabill, W., and Tonelli, J. (1988), Estimating forest biomass and volume using airborne laser data, *Remote Sens. Environ.* 24:247–267.

McCuen, R. H., and Snyder, W. M. (1986), *Hydrologic Modeling: Statistical Methods and Applications*, Prentice-Hall, Englewood, NJ, 568 pp.

Menenti, M., and Ritchie, J. C. (1992), Estimation of effective aerodynamic roughness with altimeter measurements, in *IGARRS' 92 Proceedings*, Vol. II, The Institute of Electrical and Electronic Engineering, Inc., Piscataway, NJ, pp. 1508–1510.

Menenti, M., and Ritchie, J. C. (1994), Estimation of effective aerodynamic roughness of Walnut Gulch watershed with laser altimeter measurements, *Water Resour. Res.* 30:1329–1337.

Penny, M. F., Billard, B., and Abbot, R. H. (1989), LADS—the Australian Laser Airborne Depth Sounder, *Int. J. Remote Sens.* 10:1463–1479.

Ritchie, J. C., and Jackson, T. J. (1989), Airborne laser measurements of the surface topography of simulated concentrated flow gullies, *Trans. Am. Soc. Agric. Eng.* 32:645–648.

Ritchie, J. C., Everitt, J. H., Escobar, D. E., Jackson, T. J., and Davis, M. R. (1992), Airborne laser measurements of rangeland canopy cover, *J. Range Manage.* 45:189–193.

Ritchie, J. C., and Weltz, M. A. (1992), Using an airborne laser to measure vegetation properties, in *Technical Papers of the 1992 ACSM-ASPRS Annual Convention*, Vol. 4, American Society of Photogrammetry and Remote Sensing, Bethesda, MD, pp. 395–405.

Ritchie, J. C., Evans, D. L., Jacobs, D. M., Everitt, J. H., and Weltz, M. A. (1993a), Measuring canopy structure with an airborne laser altimeter, *Trans. Am. Soc. Agric. Eng.* 36: 1235–1238.

Ritchie, J. C., Jackson, T. J., Grissinger, E. H., et al. (1993b), Airborne altimeter measurements of landscape properties, *Hydrol. Sci. J.* 38:403–416.

Schreier, H., Lougheed, J., Tucker, C., and Leckie, D. (1985), Automated measurement of terrain reflection and height variations using an airborne laser system, *Int. J. Remote Sens.* 6:101–113.

Seshamani, R. (1993), A satellite-borne laser altimeter for digital terrain modelling, *Int. J. Remote Sens.* 14:3133–3135.

Weltz, M. A., Ritchie, J. C., and Fox, H. D. (1994), Comparison of laser and field measurements of vegetation heights and canopy cover, *Water Resour. Res.* 30:1311–1319.