

DESIGN, CAPABILITIES AND USES OF LARGE-FOOTPRINT AND SMALL-FOOTPRINT LIDAR SYSTEMS

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ABSTRACT

The literature on airborne scanning lidars describes several types, two of which, small-footprint and large-footprint lidar, are used in terrestrial applications. They have evolved from similar roots for different purposes. This paper summarizes their purposes, design, functioning, capabilities and current and potential uses. Small-footprint lidars have footprints 10-90cm in diameter and record 1-5 reflection peaks from each pulse of light. Large-footprint lidars have footprints 10-25m in diameter and record a full digitized reflected waveform from each pulse. Data from small-footprint lidars are readily used to create high resolution, 1x1m to 3x3m, DTMs (digital terrain models) and characterize vegetation canopy of relatively small areas. Data from large-footprint lidars, generally at a coarser resolution, can be used to characterize topography of mineral surfaces or ice, and vertical vegetation canopy structure of larger areas, including those with relatively dense foliage. Small-footprint lidars are commonly used for surveying electric transmission lines, creating DTMs for right-of-ways for roads, pipelines, other transportation corridors, forested areas, landscape planning, areas with difficult access and hazards (especially floods) assessment and mitigation planning, and recently, 3-D modeling of urban and suburban landscapes and forest stand characterization. Large-footprint lidars are used for measuring topography and creating DTMs over relatively large areas and characterizing forest stand structure over large areas including those with very dense canopies.

1 INTRODUCTION

Terrestrial uses of lidar are increasing and have the potential to expand much farther. This potential was recognized in the published literature about 20 years ago when LIDAR was used to map forests in Central America (Arp et al., 1982). The Canadian Forestry Service also recognized this in the early 1980's and conducted extensive studies of a laser altimeter profiler to characterize height and canopy closure of forest stands (Aldred & Bonnor, 1985).

Airborne scanning lidars all share a laser rangefinder, inertial navigation system and global positioning system mounted in a fixed wing airplane or a helicopter. The laser rangefinder scans the land below the advancing plane. Return times, and orientations of reflections are recorded and calculated so that footprint locations can be calculated with high accuracies in horizontal and vertical directions.

This paper considers airborne scanning lidar (ALS) systems currently or soon to be used in terrestrial applications. These systems have been described in several papers, including most

recently in the ISPRS Journal of Photogrammetry and Remote Sensing (ISPRS, 1999). Baltsavias (1999), Wehr and Lohr (1999) and other papers in this issue do a great service in documenting the current state of small-footprint lidar technology and the reader is referred there for further information on those lidars. Recent, current and future large-footprint lidars designed for terrestrial use are described by (Blair et al., 1994; Blair et al., 1999; Harding et al., 1999), and on the web site of the Vegetation Canopy Lidar (Dubayah et al., 1999) which is planned for launch in 2000. Other large-footprint lidars used for surveying ice sheets and glaciers are described on the World Wide Web (GLAS Team, 1999; Krabill et al., 1999a; SOAR Staff, 1999). The Shuttle Laser Altimeter, last flown in 1997 (Garvin et al., 1998), and lidars used for bathymetric (Irish & Lillycrop, 1999), atmospheric (Matrosov et al., 1998), and extraterrestrial (Kreslavsky & Head, 1999) purposes are not discussed here. Large-footprint and small-footprint lidar systems have different purposes, which lead to different designs, capabilities and uses. The remainder of this paper explores these features.

Table 1. Primary Purposes of Two Types of Lidar Systems.
Not all lidars in each category share all purposes for that category.

	Small-footprint	Large-footprint
Common Goals	– ground surface elevation, DTMs – canopy top elevation	– ground surface elevation, DTMs – canopy top elevation
Different Goals	– .5-3m horizontal resolution	– 10-170m horizontal resolution – vertical distribution of canopy surfaces

2 PURPOSES OF TWO TYPES OF LIDARS

The biggest differences in purposes of small- and large-footprint lidars are in scale, types of terrain surveyed and vegetation characterization. Small-footprint lidars are required to be able to sense relatively small features, and large-footprint lidars are required to characterize complete vertical canopy structure or are used for measuring ice sheet elevations (Table 1).

Both types of lidars evolved from early profiling lidars that returned a single first reflection (Aldred & Bonnor, 1985; Arp et al., 1982; Schreier et al., 1985) and bathymetric lidars typically operated in profiling mode (Jensen et al., 1987; MacLean & Krabill, 1985; Nelson et al., 1984). From these beginnings small-footprint lidars developed to meet needs of geotechnical applications such as road and pipeline right of ways, large-scale DTMs, surveys of high-power electric transmission lines and to generate 3-D urban models

(Axelsson, 1999; Flood & Gutelius, 1997; Wagner, 1995). Their use for these purposes has expanded greatly in the last three-four years. Several large footprint lidars have been developed by NASA in the last six years towards the ultimate purpose of a satellite system to survey earth topography and vegetation height and cover. They are designed with footprints large enough to usually capture the top of one tree canopy and the ground in one pulse and can be used to map topography, vegetation height and canopy height profile (Blair & Coyle, 1996; Dubayah et al., 1999; Harding & Roark, 1999). Other scanning lidars are used to accurately measure elevations of ice sheets and glaciers (Krabill et al. 1999; Echelmeyer et al., 1996).

3 DESIGN

The different mix of purposes (Table 1) has led to different designs and functioning (Table 2). In large-footprint lidars these purposes lead to greater horizontal spacing, larger footprint size and digitization of full waveform reflections. More widely spaced footprints allow covering the desired area

Table 2. Differences in Design and Function of Two Types of Lidar Systems, Typical Values.

	Small-footprint, discrete return ^{1/}	Large-footprint, waveform return ^{2/}
Horizontal point spacing, m	.2-3	10-25
Footprint diameter, meter	0.2-0.9	10-70
Reflection collection	1-5 discrete reflections, separated by minimum 1.5-2m	full waveform digitization
Energy, mJoule/pulse	.0125-.2	(.012-.02) 5-75
Pulse rate, kHz	5-15	0.04-0.5
Flying height, km	0.2-1.0	4-400
Swath width, m	70-1200	800-8000(discontinuous)
Platform	helicopter, fixed wing	fixed wing, earth orbit

^{1/}(Baltsavias, 1999a) and e-mail communication with several lidar firms.

^{2/}(Blair et al., 1999; Dubayah et al., 1999; GLAS Team, 1999; Krabill et al., 1999a; SOAR Staff, 1999).

at a lower pulse rate reducing sizes of large data files. The lower pulse rate facilitates building systems with greater energy per pulse. Greater pulse energy allows greater operating height and so large-footprint systems are the reasonable choice for orbital platforms. Greater platform height can be a primary design goal. This in turn allows a greater swath width.

4 CAPABILITIES

The different functioning of these systems leads to different capabilities (Table 3). The closer shot spacings of small-footprint lidars allow them to resolve finer topographic details and create finer DTMs. Their lower flying altitudes and generally narrower swaths may make them less economical for covering very large areas. Small footprints are less likely to find a canopy opening and in dense vegetation most shots do not. Large-footprint lidars with their wider footprint spacing and greater platform heights may be better for characterizing topography of larger areas. Also, the full reflected waveform they capture, provides a measure of the vertical distribution of reflecting surfaces. In contrast most small-footprint lidars capture only the first or first and last reflection, though several are capable of capturing intermediate reflections.

The problem with dense vegetation

Dense vegetation near the ground may be impenetrable to small-footprint lidars that have a minimum trigger distance between successive returns. If the lidar detects a return at 1.5 m above the ground and the minimum trigger distance between returns is 2 m then it will not detect the ground. In these cases the top surface of a dense low-lying vegetation

layer may be interpreted as the ground. This problem is probably worse when there is a dense forest canopy and a dense understory. Such vegetation strata occur in the moist climate of the Pacific Northwest of USA where conifer-dominated stands can have thick shrub understories (Franklin & Dyrness, 1973). In one portion of a study area in Washington, USA, with dense overstory, preliminary analyses indicate only 1-5% of lidar shots reached the ground (J.E. Means, unpublished data). In this case the true resolution of a derived DTM will be much reduced. One approach to compensate for this is to use a very small footprint size, e.g., 10cm, and a high shot density so that hopefully an acceptable number of shots will not encounter reflecting surfaces within their minimum trigger distance above the ground.

Large-footprint lidars work around this problem of dense vegetation because somewhere in their large footprint are one or more small openings to the ground that taken together allow enough photons to be reflected from the ground to provide a discernible peak in the return waveform. The large footprint and full waveform work together to this effect as both are needed. This effect can be seen in the success of Figure 1.

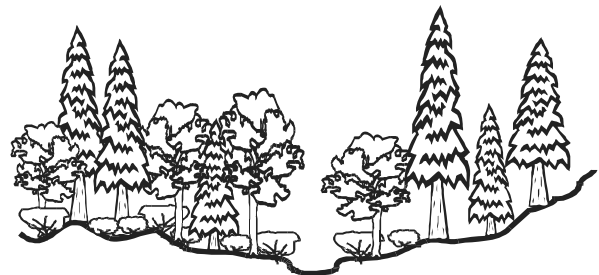


Figure 1.

Table 3. Capabilities of Two Types of Lidar Systems.

Small-footprint, discrete return	Large-footprint, waveform return
– Accurate elevations, 15-30cm with care – Closer shot spacing, .2-10m – Resolve finer topographic details – Create DTMs 5x5 to 2x2m and finer – Probably less economical creating DTMs of very large areas, e.g., 10's-100's km² – Fewer shots penetrate dense vegetation, 25-5% or less depending on cover percent – Difficulty making accurate DTMs under dense canopies – To get vegetation heights must first build DTM	– Accurate elevations, 15-30cm with care – Farther shot spacing, 2-170m – Not resolve fine topographic details – Create DTMs 10x10 to 25x25m – Probably more economical creating DTMs of very large areas, e.g., 10's-100's km² – Distinguish ground in many or most pulses through dense vegetation – Relatively effective creating DTMs under dense canopies – Ground elevation and vegetation height measured in one shot
– Data on vegetation height profile must be synthesized from many shots or returns	– Data on height profile of canopies obtained directly

Riparian zone showing shading by streamside trees. Note the dense canopy and understory on the left side may make it very difficult for small-footprint lidar to obtain reflections from the ground. LVIS in detecting the ground over 99% of the time in Sequoia National Forest in California and at least 90% of the time in the dense rainforests of La Selva Biological Research Station, Costa Rica (Blair et al., 1999).

5 USES

The different capabilities of these lidar classes give rise to different current and potential uses (Table 4). Small-footprint lidars are used primarily for creation of DTMs. These can be for road, rail or pipeline right-of-ways, open pit mines, and other uses including more recently, surveys of cities that include accurate building positions. Change detection is an emerging capability of small-footprint lidars and development of this capability in urban areas is occurring (Murakami et al., 1999). Creation of DTMs under forests and other vegetation is still a challenge. Most companies that offers lidar services

have developed this capability, though details are closely guarded. Additionally, approaches to creating DTMs have been developed in Europe at universities (Axelsson, 1999; Kraus & Pfeifer, 1998). Vegetation height and volume have been measured with good success using small-footprint (Jensen et al., 1987; Naesset, 1997a; Naesset, 1997b) and large foot-print lidars (Lefsky et al., 1999; Means et al., 1999). Forestry applications of small-footprint lidar have a bright future that is currently being explored.

Future uses

Data fusion Integration of lidar data with image data offers great potential for applications in feature recognition and forestry because the two types of information are so complementary. Lidar provides structural information, such as height, cover density and vertical distribution, while imagery provides information on composition such as roof type, landcover type, species groups and proportions of broadleaves conifers and shrubs, herbs or grass. Progress made in integrating lidar with raster imagery to make 3-D

Table 4. Uses of Two Different Types of Lidar Systems.

Small-footprint, discrete return ^{1/}	Large-footprint, waveform return ^{2/}
Current uses	
– DTMs: right-of-ways for new & existing roads, high-voltage electric power lines (pre-construction, line sag, vegetation encroachment), pipelines, mines, landfills, etc. – Urban/suburban surveys, quantitative 3-D descriptions including vegetation, buildings – Change detection of surveyed features – Forest tree height, stand volume – Integration with raster imagery and airphotos	– DTMs and topography: glaciers, volcanoes (hazards assessment, erosion, accretion), extensive areas – Change detection of surveyed features – Forest stand height, canopy cover, biomass, basal area, leaf area, including dense vegetation
Potential future uses and developments	
– Forest biomass, canopy cover, wildland fuels – River/stream: riparian vegetation (height, shade), valley floor and channel morphology (above water) – Wildlife habitat – Agricultural field drainage, crop height development – Standards for accuracy and performance – Co-collection with co-registered imagery using digital cameras, multi- & hyperspectral sensors – More automated DTM creation and integration with imagery	– Global coverage of topography, ice sheets, vegetation height & roughness – Integration and coregistration with raster imagery

^{1/} References include (Ackermann, 1999; Flood & Gutelius, 1997)

models (Haala, 1999), including automated extraction of 3-D features such as buildings (Maas & Vosselman, 1999), highlights this potential. This capability will be enhanced with co-collection and automated coregistration of raster imagery as some companies are starting to do.

There are several important opportunities for environmental assessment using lidar without evidence in the literature that they have been explored.

Canopy fuels Wildland fuels are produced by vegetation in proportion to its productivity, which can be indexed for a given vegetation type by height and canopy cover, both of which are easily measured by lidar. Canopy fuels are especially hard to inventory and are an important driver of crown fires, the most destructive and hard to control and model (Rothermel, 1991). Lidar provides much information on canopies and offers significant promise for predicting distribution in 3-D space and density of fine fuels, however, developing this potential will be a challenge.

Riparian zones Riparian vegetation is an important component of stream habitat because of its input of wood and leaves and the shade it provides, reducing heat stress on sensitive fish (Gregory et al., 1991) (Figure 1). These functions are correlated with distance from stream, vegetation height and canopy density, all of which can be assessed by lidar.

Arboreal habitat Arboreal habitat is very important for many species, some of which are threatened or endangered (Forsman et al., 1984), yet it is the most difficult type of terrestrial wildlife habitat to assess. Lidar should be very helpful here because it can index the height, density and vertical distribution of a vegetation canopy. For this to be realized, we must develop the ability to integrate small-footprint lidar reflections into a vertical canopy profile, as has been successfully achieved in Costa Rica (Blair & Hofton, 1999).

Future cost and availability

In the future costs of small-footprint lidar products should decline and types and accuracy of products should increase due to several factors. Processing into DTMs and models of features that now requires significant operator interpretation will become more automated. Competition in the industry will increase. Repetition rates of lidars will increase and associated computer costs will decrease, allowing data to be

collected more efficiently and at the higher densities needed for some applications, and/or reducing the cost per unit area. Flexibility in footprint size and spacing and in flying height will increase. A great improvement for applications to dense forest stands will be commercial availability of a lidar with a full waveform return. This will blur the difference between large-footprint and small footprint lidars.

The availability in the next few years of data from the satellite lidar, VCL (Dubayah et al., 1999), will provide every major landowner with large-footprint (25m) lidar data. Single tracks of contiguous footprints will be spaced 2 km apart over the earth's land surface between 65 degrees North and South, and this data will be publicly available. The future is bright for this new technology; we will learn much about our world (and solar system) through data lidars provide.

6 References

- Ackermann, F., 1999. Airborne laser scanning - present status and future expectations. *ISPRS J Photogram & Remote Sens* **54**(2-3):64-67.
- Aldred, A. H. & Bonnor, G. M., 1985. Application of airborne lasers to forest surveys. Petawawa National Forestry Institute. *Information Report PI-X-51*, 62 p.
- Arp, H., Griesbach, J.C. & Burns, J. P., 1982. Mapping in tropical forests: A new approach using the laser APR. *Photogram Eng & Remote Sens* **48**(1):91-100.
- Axelsson, P., 1999. Processing of laser scanner data - algorithms and applications. *ISPRS J Photogram & Remote Sens* **54**(2-3):138-147.
- Baltsavias, E. P., 1999. Airborne laser scanning: existing systems and firms and other resources. *ISPRS J Photogram & Remote Sens* **54**(2-3):164-198.
- Blair, J. B. & Coyle, D. B. 1996. Vegetation and topography mapping with an airborne laser altimeter using a high-efficiency laser and a scannable field-of-view telescope. In: *Proceedings of the Second International Airborne Remote Sensing Conference and Exhibition*, Vol. II., Environmental Research Institute of Michigan, Ann Arbor, Michigan, 2:403-407.
- Blair, J. B., Coyle, D. B., Bufton, J. L. & Harding D. J. 1994. Optimization of an airborne laser altimeter for remote sensing

of vegetation and tree canopies. In: *Surface and atmospheric remote sensing: technologies, data analysis and interpretation. International Geoscience and Remote Sensing Symposium (IGARSS)*, California Institute of Technology, Pasadena, Calif., 939-941.

Blair, J. B. & Hofton, M. A., 1999. Modeling laser altimeter return waveforms over complex vegetation using high_resolution elevation data. *Geophys Res Let* **26**(16):2509-2512.

Blair, J. B., Rabine, D. L. & Hofton, M. A., 1999. The laser vegetation imaging sensor: a medium_altitude, digitisation_only, airborne laser altimeter for mapping vegetation and topography. *ISPRS J Photogram & Remote Sens* **54**(2-3):115-122.

Dubayah, R., Blair, J. B., Bufton, J. L., Clark, D. B., Knox, R. G., Luthcke, S. B., Prince, S. & Weishampel, J., 1999. Vegetation Canopy Lidar Mission. <http://www.inform.umd.edu/Geography/vcl/> World Wide Web. University of Maryland.

Echelmeyer, K. A., Harrison, W. D., Larsen, C. F., Sapiano, J., Mitchell, J. E., DeMallie, J., Rabus, B., Adalgeirsdottir, G. & Sombardier, L. 1996. Airborne surface profiling of glaciers: a case_study in Alaska. *J Glaciol* **42**(142):538-547.

Flood, M. & Gutelius, B., 1997. Commercial implications of topographic terrain mapping using scanning airborne laser radar. *Photogram Eng & Remote Sens* **63**(4):327-366.

Forsman, E., Meslow, E.C. & Wight, H.M., 1984. Distribution and biology of the spotted owl in Oregon. Wildlife Society, Bethesda, MD, 64 p.

Franklin, J. F. & Dyrness, C. T., 1973. Natural vegetation of Oregon and Washington. Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, Portland, Oregon. *General Technical Report PNW-8*. 417 p.

Garvin, J. B., Bufton, J., Harding, D., Luthcke, J., Frawley, J. & Rowlands, D., 1998. Observations of the Earth's topography from the Shuttle Laser Altimeter (SLA): laser pulse echo recovery measurements of terrestrial surfaces. *Phys & Chem Earth* **23**(9-10):1053-1068.

GLAS Team 1999. ICESat/GLAS. <http://www.csr.utexas.edu/glas/> World Wide Web. Center for

Space Research, University of Texas at Austin.

Gregory, S.V., Swanson, F.J., McKee, W.A. & Cummins, K.W., 1991. An ecosystem perspective of riparian zones. *BioSci* **41**(8):540-551.

Haala, N., 1999. Combining multiple data sources for urban data acquisition. In: *Photogrammetric Week '99*, Fritsch D. & Spiller R., eds.), Herbert Wichmann Verlag, Heidelberg, pp. 329-340.

Harding, D. J., Blair, J. B., Rabine, D. L., & Still, D. J., 1999. Scanning Lidar Imager of Canopies by Echo Recovery (SLICER): Instrument and Data Product Description, In review. *National Aeronautics and Space Administration. Technical Memorandum*

Harding, D. & Roark, J., 1999. SLICER (Scanning Lidar Imager of Canopies by Echo Recovery) Airborne Laser Altimeter. <http://denali.gsfc.nasa.gov/research/laser/slicer/slicer.html> World Wide Web. NASA, Goddard Space Flight Center, Greenbelt, Maryland.

Hofton, M. A., Blair, J. B., Minster, J. B., Ridgway, J. R., Williams, N. P., Bufton, J. L., and Rabine, D. L., 1999. An airborne topographic survey of Long Valley caldera, CA, 1995, using scanning laser altimetry. *J Remote Sensing*

Irish J.L. & Lillycrop W.J. 1999. Scanning laser mapping of the coastal zone: the SHOALS system. *ISPRS J Photogram & Remote Sens* **54**(2_3):123_129.

ISPRS 1999. *ISPRS J Photogram & Remote Sens* **54**(2-3).

Jensen, J. R., Hidgson, M. E., Mackey, H. E., Jr. & Krabill, W., 1987. Correlation between aircraft MSS and LIDAR remotely sensed data on a forested wetland. *Geocarto Internat* **4**:39-54.

Krabill, W., Yungel, J., & Manizade, S., 1999a. Airborne Topographic Mapper. <http://aol.wff.nasa.gov/aoltm.html> World Wide Web. National Aeronautics and Space Administration.

Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W. & Yungel, J. 1999b. Rapid thinning of parts of the southern greenland ice sheet. *Sci* **1475**:1522-1524.

- Kraus, K. & Pfeifer, N., 1998. Determination of terrain models in wooded areas with airborne laser scanner data. *ISPRS J Photogram & Remote Sens* 53:193-203.
- Kreslavsky, M., & Head, J.W. 1999. Kilometer-scale slopes on Mars and their correlation with geologic units: Initial results from the Mars Orbiter Laser Altimeter (MOLA). *J Geophys Res* 104:911-924.
- Lefsky, M. A., Harding, D., Cohen, W. B., Parker, G., & Shugart, H. H., 1999. Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA. *Remote Sens Env* 67(1):83-98.
- Maas, H. G., & Vosselman, G., 1999. Two algorithms for extracting building models from raw laser altimetry data. *ISPRS J Photogram & Remote Sens* 54(2_3):153-163.
- MacLean, G. A., & Krabill, W. B., 1985. Gross merchantable timber volume estimation using an airborne LIDAR system. *Can J Remote Sens* 12(1):7-18.
- Matrosov, S., Heymsfield, A., Kropfli, R., Snider, Martner, Piironen, P., & Eloranta, E.W., 1998. Comparisons of ice and cloud properties obtained by remote and direct methods. *J Atmos & Ocean Tech* 15:184-196.
- Means, J. E., Acker, S. A., Harding, D. J., Blair, J. B., Lefsky, M. A., Cohen, W. B., Harmon, M. E. & McKee, W. A., 1999. Use of large_footprint scanning airborne lidar to estimate forest stand characteristics in the western Cascades of Oregon. *Remote Sens Env* 67(3):298-308.
- Murakami, H., Nakagawa, K., Hasegawa, H., & Shibata, T., 1999. Change detection of buildings using an airborne laser scanner. *ISPRS J Photogram & Remote Sens* 54(2-3):148-152.
- Naesset, E., 1997a. Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS J Photogram & Remote Sens* 52(2):49-56.
- Naesset, E., 1997b. Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sens Env* 61(2):246-253.
- Nelson, R., Krabill, W., & Maclean, G., 1984. Determining forest canopy characteristics using airborne laser data. *Remote Sens Env* 15:201-212.
- Nelson, R., Oderwald, R. & Gregoire, T. G., 1997. Separating the ground and airborne laser sampling phases to estimate tropical forest basal area, volume, and biomass. *Remote Sens Env* 60(3):311-326.
- Rothermel, R.C., 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. USDA Forest Service, Intermountain Research Station, Fort Collins, CO. *Research Paper INT-438*, 46 p.
- Schreier, H., Lougheed, J., Tucker, C. & Leckie, D., 1985. Automated measurements of terrain reflection and height variations using an airborne laser system. *Int J Remote Sens* 6:101-113.
- SOAR Staff 1999. Support Office for Aerogeophysical Research. <http://www.ig.utexas.edu/research/projects/soar/soar.html> World Wide Web. Institute for Geophysics, University of Texas at Austin.
- Wagner, M. J., 1995. Seeing in 3_D without the glasses. *Earth Observ Mag* (July):51-53.
- Wehr, A. & Lohr, U., 1999. Airborne laser scanning - an introduction and overview. *ISPRS J Photogram & Remote Sens* 54(2-3):68-82.