Lidar remote sensing for forestry applications: The Indian context

M. D. Behera and P. S. Roy*

Lidar remote sensing has the unique advantage of providing three-dimensional data through direct and indirect retrievals with unprecedented accuracy. It has enormous potential for forest ecological research, because it directly measures the physical attributes of vegetation canopy structure that are highly correlated with the basic plant community measurements. This technology is new and is restricted to only few countries of the world and has not yet properly reached to many countries including India. In India, this technique could be utilized to address various aspects of forest ecosystem management, not possible earlier with the data available from aerial photographs, optical and radar satellites or even by ground measurements. This article advocates that forest management strategy in India should be based on reliable, lidar-derived database on forest structure and its productive potentials.

LIDAR (light detection and ranging) remote sensing is a breakthrough technology for forest studies. It offers a great potential for conservation and management of India's invaluable forest wealth. For both economic and environmental reasons, it is critical to measure and understand the spatial organization of forest ecosystems. Typical remote sensing images allow analysing various attributes of forests, but are limited in their ability to represent spatial patterns only in two-dimensional space. The advantage of using lidar remote sensing for forestry applications is that it provides data on three-dimensional forest structures characterizing vegetation height, vertical distribution of canopy material, crown volume, sub-canopy topography, biomass, vertical foliage diversity and multiple layers, height to live crown, large tree density, leaf area index, and physiographic or life form diversity through direct and indirect retrievals. Thus, lidar technology offers an emerging challenge to the management of India's forests, the panorama of which ranges from evergreen tropical rain forests in the Andaman and Nicobar Islands, the Western Ghats and the north-eastern states, to dry alpine scrub high in the Himalaya to the north. The technology could be utilized to address various aspects of forest ecosystem management, not possible previously with the data available from aerial photographs, optical and radar satellites or even by ground measurements. If cautiously planned, lidar can form the most scientific and accurate means of forest management in the country, viz. the three-dimensional data set can be used to re-define the only existing 'forest types' classification[1] that groups Indian forests into 16 major and 22 minor forest types based on structure, physiognomy and floristic properties of vegetation. This article aims at providing the recent trends in lidar applications to forestry and discusses the prospects of this technology in the Indian context. The term 'lidar' and 'laser' have been defined along with the basic principles and advantages of lidar remote sensing. Various research issues have been analysed in terms of studies done using helicopter/airborne, small/large footprint and discrete/continuously-pulsed laser sensors across the globe. The objective of this article shall be achieved, if various researchers/planners from different government and non-governmental organizations would take initiatives and start preparing groundwork for utilizing the marvels of this technology, and if various teaching/training organizations involved in remote sensing applications to forestry, would include details of the lidar technology into the course curriculum to generate trained manpower, for the greater benefit of the nation and its people.

Applications and advantages of lidar technology

Modern lidar acquisition provides surface information for the 'bare earth' and features above the surface (vegetation structures, building attributes, etc.), and is digitally ready for many GIS applications hitherto. Wehr and Lohr[2] reviewed different applications of lidar; (i) mapping of electrical transmission lines and towers, including

M. D. Behera is in the Regional Remote Sensing Service Centre, Indian Institute of Technology Campus, Kharagpur 721 302, India; P. S. Roy is in the Indian Institute of Remote Sensing, 4, Kalidas Road, P.B. No. 135, Dehradun 248 001, India
*For correspondence. (e-mail: mukundbehera@yahoo.co.uk)

ground/tree clearance; (ii) mapping of corridors, e.g. roads, railway tracks, pipelines, waterways, landscapes; (iii) generation of DTM, especially in forested areas (for road and path planning, study of drainage patterns, etc.); (iv) measurements of coastal areas, including dunes and tidal flats and determination of coastal change and erosion; (v) high accuracy and dense measurement applications, e.g. flood mapping, DTM generation and volume calculation in open pit mines, road design and modelling; (vi) DTM and DSM generation in urban areas, automated building extraction, generation of 3D city models for planning of relay antenna locations in wireless telecommunication, urban planning, microclimate models, propagation of noise and pollutants; (vii) rapid mapping and damage assessment after natural disasters like hurricanes, earthquakes and landslides; (viii) measurement of snow- and ice-covered areas, including glacier monitoring; (ix) measurement of wetlands; (x) characterizing vegetation structure attributes; (xi) plant growth monitoring in precision farming; (xii) hydrographic surveys in depths up to 70 m; (xiii) snow accumulation for avalanche risk estimation; and (xiv) 3D models for movie, video and computer animation, 3D models for architectural design and simulation, visualization and fly- or walk-through. The various advantages of lidar technology are: (a) higher accuracy (up to the order of 10–15 cm in the vertical and 50–100 cm in the horizontal); (b) weather independence (being an active sensor, it can collect data at night and clear weather conditions); (c) capability of canopy penetration (unlike photogrammetry, lidar can see below canopy in forested areas and provide topographic measurements of the surface underneath); (d) higher data density; (e) independent of ground control points (only one or two GPS ground stations are required for improving the GPS accuracy by the differential method, thus proved to be an ideal method for inaccessible or featureless areas like wastelands, ice sheets, deserts, forests and tidal flats); (f) lesser time for data acquisition and processing (the data capture and processing time is significantly less for lidar compared to other techniques); (g) minimum user interference (as most of the data capture and processing steps are automatic except the maintenance of the ground GPS station); and (h) provides additional data (e.g. laser-derived intensity images help in classifying the terrain features).

Lidar system

Lidar is an active remote sensing technique using laser light. The lidar system measures the round-trip time for a pulse of laser (light amplification by stimulated emission of radiation) energy to travel between the sensor and the target. This incident pulse of energy interacts with the earth features and is reflected back to the target. The travel time of the pulse from initiation until it returns to the sensor is measured, and it provides a distance or range from the instrument to the object (hence the common use of the term 'laser altimetry' which is now generally synonymous with lidar). Since the speed of light is a constant, the time from pulse emission to pulse return can be accurately measured (Table 1). The intensity or power of the return signal depends on several factors: the total power of the transmitted pulse, the fraction of laser pulse that is intercepted by a surface, the reflectance of the intercepted surface at the laser's wavelength and the fraction of reflected illumination that travels in the direction of the sensor. Lidars for terrestrial applications generally operate in the wavelength range of 900–1064 nm (ref. 3), where vegetation reflectance is high[4]. Lidar systems incorporate rapid laser pulsing with GPS for position (x, y, z) and an inertial measurement unit (IMU) for orientation (pitch, yaw and roll) of the sensor. As with any GPS activity, the lidar system requires initialization with a surveyed-point, ground GPS base location and differential post-processing corrections. In addition, a tested alignment process for the GPS position of the sensor and the IMU orientation parameters is required to verify the accuracy of the lidar data sets. These systems are able to record up to five returns per pulse, which demonstrates the value of lidar to discriminate not only the top and bottom points of canopy, but also surfaces in between, viz. understorey.

A typical laser scanner can be subdivided into the following key units: laser ranging unit, opto-mechanical scanner, control and processing unit. The ranging unit comprises the emitting laser and the electro-optical receiver (Figure 1 *a*, *b*). The transmitting and receiving apertures (typically 8–15 cm diameter) are mounted so that the transmitting and receiving paths share the same optical path. This assures that object surface points illuminated by the laser are always in the field of view (FOV) of the optical receiver. The narrow divergence of the laser beam defines the instantaneous field of view (IFOV). Typically, the IFOV ranges from 0.3 mrad to 2 mrad. The theoretical physical limit of the IFOV is determined by diffraction of light, which causes image blurring. Therefore, the IFOV is a function of the transmitting aperture and wavelength of light.

Laser ranging

Lasers have two advantages over radar range measurement: e.g. (i) high energy pulses can be realized in short

Table 1. Lidar echo time to measurement range conversion (speed of the light c = 3.0E8 m/s)

1 ns	0.15 m	5.9 in
1 μs	150 m	492 ft
10 μs	1.5 km	0.93 statute mile (0.81 n mile)
100 μs	15 km	9.32 statute mile (8.1 n mile)
1000 μs (1 ms)	150 km	93.2 statute mile (81 n mile)

intervals, and (ii) their comparatively short wavelength light can be highly collimated using small apertures. Young[5] explained that using a powerful highly directional optical light beam can be generated which is often highly coherent both in space and time domain. The level of coherence is dependent on the laser. Gas and solid state lasers offer higher coherence than semi conductor lasers. A lidar may also be built up by xenon or flash lamps which are not laser sources. Two major ranging principles are applied in range measurements: (a) Pulse ranging principles – Mostly pulsed lasers are used currently. They are usually solid-state lasers which produce high power output. They can be pumped with light from xenon flash tubes, arc lamps, metal-vapour lamps and laser diodes, which are especially applied for pumping airborne lasers. (b) Continuous wave – It ranges by measuring the phase difference between the transmitted and the received signal backscattered from the object surface. This method is applied with lasers that continuously emit light.

The accuracy of 3D coordinates of airborne laser systems depends on many factors[6]. The main factors are the accuracy of range, position of the laser beam and direction of the laser beam. Since the results are usually in WGS84, the final results also depend on the accuracy of the transformation from WGS84 to the local coordinate system, including corrections for the geoid's undulations, which can be significant with respect to the accuracy potential of ALS. In addition, since different sensors measure range, position and beam direction, any time misregistration errors will also influence the results. Independent accuracy investigations[7,8] demonstrated that depending on terrain slope and cover, lower accuracies are achieved especially in planimetry. Another open topic is accuracy investigations, especially for the rotation angles for high (> 1000 m) altitudes.

Space-borne lidars

The LITE mission

LITE (Lidar In-space Technology Experiment) was flown on the space shuttle *Discovery* (NASA) as part of the STS-64 mission in an inclined orbit, which allowed observation of six of the seven continents and operated for 53 h (with 45 h data take) between 9 and 20 September 1994. These data presented detailed global view of

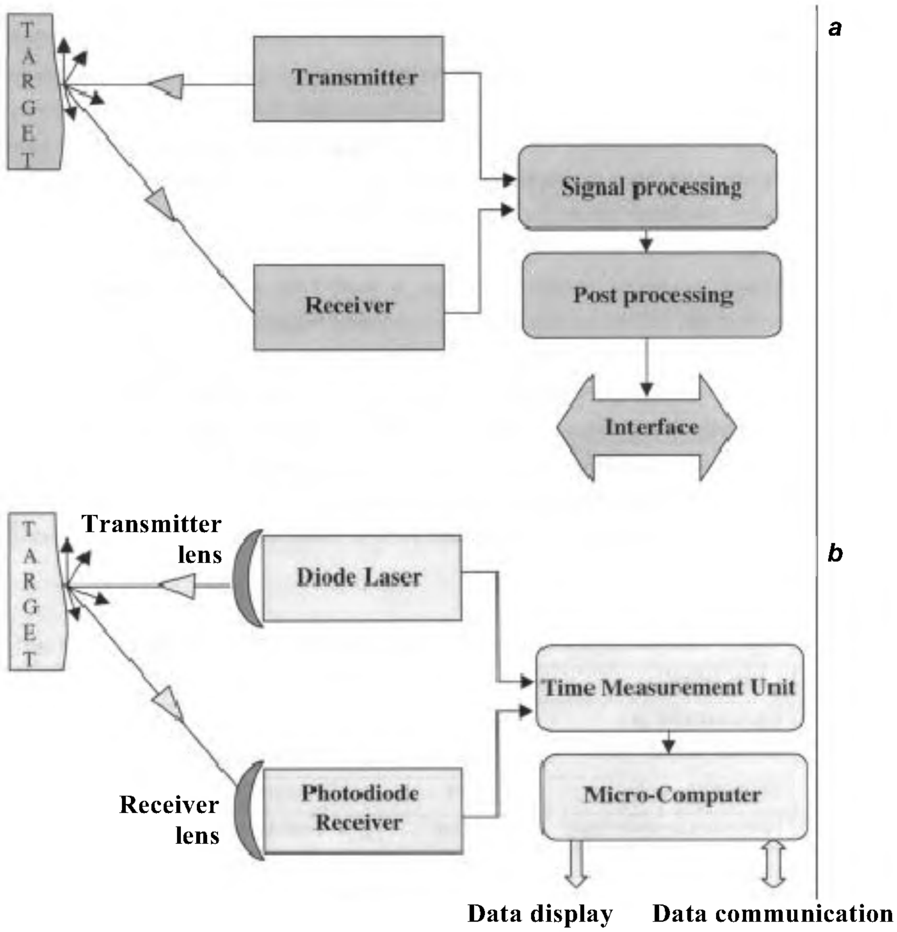

Figure 1. Different components of a typical lidar system.

vertical structure of clouds and aerosols[9–11], including various environmental phenomena, viz. biomass burning (Figure 2) and validated key enabling technologies required for operational space-borne lidar.

The VCL mission

The Vegetation Canopy Lidar (VCL) was the first selected mission of National Aeronautics and Space Administration's (NASA's) new Earth System Science Pathfinder programme[12]. Its primary scientific objectives were (i) land cover characterization for terrestrial ecosystem modelling, monitoring and prediction, (ii) land cover characterization for climate modelling and prediction, and (iii) production of a global reference data set of topographic spot heights and transects. VCL was planned to be an active lidar remote sensing system consisting of a five-beam instrument with 25-m contiguous along-track resolution (Table 2). The five beams are in a circular configuration 8 km across and each beam traces a separate ground track spaced 2 km apart, eventually producing 2 km coverage between 65° N and S with three core measurement objectives, viz. (i) canopy top height, (ii) vertical distribution of intercepted surfaces, e.g. leaves and branches, and (iii) ground surface topographic elevation. But, unfortunately, NASA has recently cancelled the launch of this satellite into its proposed orbit.

Forestry studies using lidar

Forestry studies using lidar are restricted to only few countries and researchers around the globe. Table 3 lists some lidar-based forestry studies and their characteristics. Lefsky *et al.*[3] reviewed lidar remote sensing for ecosystem studies, highlighting the latest researches. A survey of ALS systems and firms by Baltsavias[13] revealed few users, viz. USA (12), Canada (7), Japan (5), Australia (3), South Africa (1) and Europe (19-Belgium, Germany, Norway, Russia, Sweden, The Netherlands, UK and Italy), for the lidar technology.

As vertical component (*z*-axis) measurement is the backbone of lidar technology, this characteristic is exploited in a straightforward way for tree height estimation in comparison to the ground. Tree canopy height is obtained by subtracting the elevations of the first and last returns. Vegetation height is a function of species composition, climate and site quality, and can be used for land cover classification or in conjunction with vegetation indices. If coupled with species composition and site quality information, height serves as an estimate of stand age or successional stages. Like simple height estimate, the vertical distribution of laser returns provides a basis

Table 2. VCL data characteristics and quality[12]

Swath width	8 km
Number of beam tracks	3
Footprint (at 400 km)	25 m (60 @ mu @rad)
Footprint spacing	Contiguous over land (approx.)
Track spacing	4 km
Pulses per second	290 over land (approx.)
Wavelength	1064 nm
Coverage	Between 67° N and S
Elevation accuracy	< 1 m in low slope terrain
Waveform digitization	250 mega samples/s
Samples per waveform	10–200, average = 50
Sample precision	10 bits
Pulse detection dynamic range	100 : 1

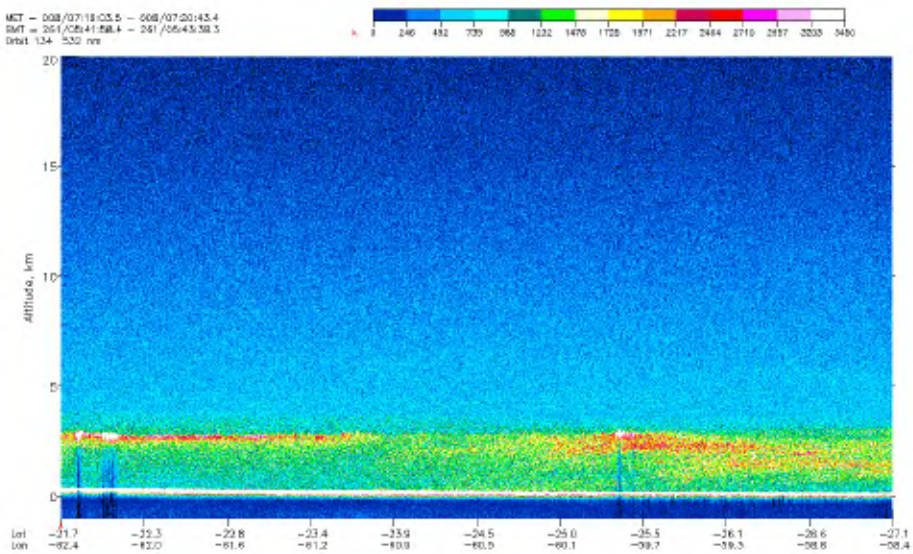

Figure 2. LITE observation of biomass burning over South America (Bolivia, Paraguay and Uruguay). © Environment Canada/NASA Langley Research Center.

to classify vegetation and to estimate other important canopy characters like canopy cover and crown volume (foliage, trunk, twigs, branches). Since the vertical components of stands change with age, older stands can be characterized by canopy gaps. And trees of multiple ages and sizes exhibit an even distribution of canopy components. Lidar such as LVIS measure full return wavelength estimate sub-canopy and *bare* earth topography directly[12]. Lidar can accurately estimate the rate of photosynthetically active radiation (PAR) absorption and define the location and depth of the zone, where the maximum rate of PAR absorption occurs[14]. Lidar data provide input for modelling of biophysical parameters to estimate aboveground biomass with reasonably high accuracy[15–22]. Vertical foliage diversity can be derived from lidar data using extinction coefficient[23]. But the problem in deriving vertical foliage diversity is light obscuration through dense forest; shaded sparse layers become close to the detection limits of sensors. The lack of a completely general quantitative relationship between lidar waveforms and foliar profiles does not preclude developing empirical relationships useful in particular regions and stand types, thus offering a challenge for more work in varied conditions.

Table 3. Some lidar-based forestry studies and their characteristics

Vegetation parameter	Reference	Methodology	Forest/vegetation type	Lidar system	Remarks
Vegetation height	45	Comparison with field measurement	Temperate deciduous and desert scrub (tiger bush), Niger, Africa	Agricultural Research Service profiling laser; gallium-arsenide diode laser; 904 nm	Vegetation of short stature (~ 1 m) can be measured
Tree height and stand volume	18	Comparison with ground measurement	Coastal Scots pine trees, Sweden	Helicopter-borne, frequency-doubled Nd: YAG laser; 532 and 1064 nm	Lidar data underestimated mean tree height; optical footprint size was found to change data acquisition times
Basal area, volume and biomass	17	Developed a canopy structure model	Primary tropical wet forest, USA	NASA P-3a oceanographic lidar; frequency-doubled Nd: YAG laser; 532 nm	Good agreement in comparison to field measurements; predicted use for reconnaissance level survey of remote forest areas worldwide
Biomass and volume	16	Comparison with forest mensuration-based data	Southern pine forest, USA	NASA P-3a oceanographic lidar; frequency-doubled Nd: YAG laser; 532 nm	Species stratification did not consistently improve regression relationship
Individual tree height estimation	39	Comparison with tree crown architecture and coordinate location	Tolerant hardwood forest, Canada	Optech's ALTM 1225 airborne lidar system	No underestimation of tree height
Canopy height	46	Multi-fractal analysis	Pine Savanna, USA	–	Good level of consistency between laser and field measurement
DTM of forest area and tree height	35	DTM algorithm	Boreal forest, Norway	–	Forest road height deviated by 8.5 cm and individual tree height obtained with < 1 m standard deviation
Gross merchantable timber volume	31	Comparison with field measurement	Temperate forest, Canada	–	92% variation was observed
Basal area, AGBM and foliage biomass	21	Comparison with ground measurement	Douglas fir and western hemlock, USA	SLICER	Found very accurate estimates of basal area, aboveground biomass and foliage biomass using lidar height and cover estimates
Forest structure attributes	20	Statistics derived from CVM used for prediction	Douglas fir and western hemlock, USA	SLICER	More accurate estimation
Mean stem diameter, basal area and AGBM	22	Regression analysis and comparison with field data	Tropical wet forest, USA	LVIS, on NASA C-130 cargo plane; 1064 nm	Explaining up to 93, 72 and 93% of variance respectively

Tree height estimation

During the last 10–15 years, several experiments have been carried out in order to determine various tree height metrics and stem numbers by different airborne laser profiling and scanning systems (Table 3)[16,19,21,23–25]. Majority of the forest stand characteristics have focused on old forest stands or forests where the mean tree height exceeds about 15 m. At least in such forests, small-scale trails have revealed that both small footprint[19,24–26] and large foot print lasers[21,23] may produce quite accurate estimates of tree or canopy height and stem number. Naesset[19] found that the maximum height value of laser canopy hits for a certain fixed area could be used to estimate the mean tree height. Later, Magnussen and Boudewyn[24] advocated that, for a given crown shape and a certain plot size, there exists a certain quantile of the distribution of the canopy height of a plot that matches the tree height of interest, e.g. the mean height. Since crown shape, tree species and density that affect the relationship between the distribution of canopy height and tree height tend to vary among different plots, it is probably useful to model the mean height of dominant trees by means of several such quantiles. As a matter of fact, other variables of the distribution of canopy heights such as the mean and median values, standard deviation divided by the mean (coefficient of variation), and various quantiles have been found to be correlated with mean tree height, dominant height and other biophysical properties[17,19,21,23,25–27]. Furthermore, since the tree density will affect the relationship between height derived from the laser data and the true tree height[19], variables related to canopy density, such as the number of the canopy hits divided by the total number of transmitted pulses, will be useful in modelling of dominant tree height from laser scanner data. Multiple regression was developed, wherein multiplicative models were estimated as linear regressions in the logarithmic variables because multiplicative models and/or logarithmic transformations were found to be suitable for estimation of mean tree height and timber volume, which are related to tree density[25,28]. The procedure for estimating dominant height of entire forest stands was based on the assumption that for a certain cell size, i.e. a fixed area, there exists a certain relationship between the tree height of interest and predictor variables derived from the height distribution of laser pulses classified as canopy hits[19,24].

There are many difficulties in determining tree height using lidar data, viz. (i) Determining the exact elevation of the ground surface poses difficulties for both discrete and waveform lidar. (ii) In complex canopies, elevation returned from what appears to be the ground level in fact may be from understorey, if the understorey is dense enough to substantially obstruct the ground surface. (iii) Each type of lidar system represents difficulties in detecting the uppermost portion of the plant canopy (Table 4). (iv) Underestimation of canopy height – (a) with discrete return lidar, very high footprint densities are required to ensure that the highest portion of individual tree crowns is sampled and (b) with waveform sampling system, a large footprint is illuminated increasing the probability that treetops will be illuminated by the laser. However, the top portion of the crown in case of conifers may not always be of sufficient area to register as a significant return signal, and therefore may not be detected. Estimation of canopy cover and ground surface is often complimentary, i.e. if one is underestimated, then the other would be overestimated and vice versa. Canopy cover estimates are made using the fraction of the lidar measurements that are considered to have been returned from the ground surface[15,29]. Large footprint lidar measurements incorporating information contained in the laser return waveform have been used to derive canopy height and structure in a variety of canopy closure condi-

Table 4. Small vs large footprint lidar for mapping of vegetation attributes

Small footprint lidar	Large footprint lidar
Small diameter beams frequently miss the tree tops[27].	Large footprint beams avoid missing the tree tops frequently[43]. By increasing the footprint size to the approximate crown diameter of a canopy-forming tree (~ 10–25 m), laser energy consistently reaches the ground, even in dense forests[40].
Because of their small beam size and low flying height, mapping large areas requires extensive flying, thus adding to the budget.	Large footprint systems fly at higher altitudes and enable a wide image swath, which reduces the expense of mapping large areas on the ground[41].
Usually, small footprint systems record the first and/or last returns, thus making it difficult to determine if a particular shot has penetrated the canopy all the way to ground.	Large footprint systems digitize the entire return signal, thus providing data on the vertical distribution of intercepted surfaces from the top of the canopy to the ground.
In areas of high canopy only one in several thousands returns may be from the ground[44], thus giving rise to the risk of inaccurate height measurement relative to the ground.	This risk is reduced in case of large footprint lidars.
It may not be optimal for mapping forest structures.	This has many advantages for mapping of forest structures. But the risk is that biases from the blurring of ground and canopy can become large as well, again affecting height recovery[41].

tions[21,23]. Often, *scaling* factor is required to correct the relative reflectance of ground and canopy surfaces at the wavelength of the laser[21].

Wulder *et al.*[30], on a point and polygon basis, indicated the utility of lidar data as a sampling tool in a forest inventory context. They have also opined that increasing sampling intensity will improve precision. More research within this field is therefore required to take advantage of increased capabilities of the scanning laser systems as technology improves. Maclean and Krabill[31] adopted a photogrammetric technique – the canopy profile cross-sectional area (i.e. the total area between the ground and the upper canopy surface along a transect) for interpreting lidar data. Menenti and Ritchie[32] used a profiling laser altimeter to predict aerodynamic roughness length of complex landscapes containing a mixture of grassland areas and found good agreement with field estimates. Anderson *et al.*[33] developed an algorithm for automated measurement that is driven by a greyscale morphological analysis of a high-resolution lidar-based canopy surface model, to locate and measure individual tree crowns, and found high producer's accuracy (omission error) and user's accuracy[34] (commission error). This study explains that mathematical morphology can be used to relate the three-dimensional structure within a detailed lidar-based forest canopy surface model to the location of tree crowns. Hyyppa *et al.*[35] observed 22 cm average standard error in laser-derived DTM for a forest area and showed that individual tree heights in the dominating storey can be obtained with > 1 m standard error. Saito *et al.*[36] developed and performed characteristics of laser-induced fluorescence imaging lidar to check the laser-induced fluorescence (LIF) for Ginkgo tree, proving its potential for macroscale monitoring of trees remotely and non-destructively. Lefsky *et al.*[23] had described a new system for canopy description – CVM (Canopy Volume Method) – wherein they treated the forest canopy as matrix of *voxels* (three-dimensional pixels). Each *voxel* was defined as either containing canopy or not, and either in the brightly or dimly sunlit portion of the canopy. This information was then used to describe the quantitative and qualitative differences in canopy structure between four age-classes. This approach led to a better understanding of the structure of the old-growth forest canopy, new visualizations of the multiple canopy aspect of old-growth development and improved estimates of forest stand structure.

Nelson *et al.*[16] estimated the volume and biomass of southern pine forests using several estimates of canopy height and cover from discrete return lidar with 53 and 65% of variance in field measurements of these variables. Naesset[28] found 45–89% of variance in stand volume in stands of Norway spruce and Scots pine, using measurements of maximum and mean canopy height and cover. Nilsson[18] predicted 78% variance in timber volume for stands of even-aged Scots pine, wherein he used the height and the total power of each waveform as independent variables. Lefsky *et al.*[20,23] predicted basal area and above ground biomass (AGBM) from canopy height profile with and without applying multiple regressions. Similarly, Means *et al.*[21] estimated basal area, AGBM and foliage biomass by comparing with field plots. Drake *et al.*[22] used a set of indices describing the vertical distribution of the raw waveforms and the fraction of total power associated with the ground returns. They were able to predict field-measured quadratic mean stem diameter, basal area and AGBM with 93, 72 and 93% of variance respectively.

Discussion

It is obvious that lidar is an accurate, fast and versatile measurement technique, which can complement or partly replace other geo-data acquisition technologies and open up new, exciting areas of application. The prediction of forest parameters is either direct or indirect. For direct measurement, a characteristic such as height is estimated by first minus last return of the raw data alone or by applying a linear transformation to the raw data. Indirect estimates are most often based on first estimating a fundamental parameter such as height which is then fed into a predictive model for biomass and volume. Laser technique may prove most useful to detect changes in the above ground carbon stores of the tropics, where the most rapid and significant climate and vegetation changes are expected over the next decades. Such measurements will improve our understanding of the effects of these factors on land degradation and the hydrological and biological systems. A combination of lidar data and satellite remote sensing data could also be useful for describing biodiversity and monitoring changes in biodiversity[18]. There is a large potential for savings, if laser data and image data could be collected simultaneously, and stand delineation and characteristics usable for stratification could be derived from existing auxiliary data and automated methods[37].

Measurements from small footprint laser altimeter instruments have been useful in estimating tree height[16,18,19,24], per cent canopy cover[29], timber volume[28] and in some cases, forest AGBM. Leckie *et al.*[38] have examined combination of high density lidar and multispectral imagery for individual tree isolation and analysis. Fusion of optical remote sensing data, and/or conventional/digital aerial photographs with lidar data for three-dimensional modelling is the focus of research of a Canadian research project[39]. However, these fine-resolution sensors typically yield consistent ground returns only in relatively open forest canopies[40], thus making AGBM estimation difficult in dense tropical forests. Previous attempts to estimate tropical forest AGBM using small footprint laser altimeters were complicated by the incompatibility of data sets, such as the lack of coincident field- and laser-derived data[17,27]. New large footprint lidar instruments may be able to overcome the saturation problems of other remote sensing instruments[41]. It is expected that future work will integrate remotely sensed individual tree measurements into sampling design in order to optimize forest inventory programmes.

It may be concluded that lidar is an accurate tool for measuring topography, vegetation height and cover as well as complex attributes of canopy structure and function. It is expected that the above-mentioned findings will continue to be corroborated in a variety of biomes, with similar results. It may be useful in detecting habitat features associated with particular species, including rare and endangered ones. Different indices of structural complexity could be useful to identify areas of probable high biodiversity, thus providing inputs to GAP analysis programmes. Identifying various classes of forest structures and canopy gaps associated with varying fire behaviour, may help in fire prevention. In future, it would boost the study of canopy science and physical attributes of vegetation canopy structure. The presence of specific organisms and the richness of wildlife communities may be highly dependent on the three-dimensional spatial pattern of vegetation, especially in systems where biomass accumulation is significant. Individual animal and bird species are invariably associated with specific three-dimensional features in forests. Other functional aspects such as forest productivity may be related to forest canopy structure, which is measured precisely from lidar data.

Wake-up call

It is amply clear that the lidar technique has become a prominent tool to collect accurate high-resolution, three-dimensional data. In addition, the typical characteristics of lidar data have opened up the possibility of using them for many other applications which were not thought of earlier. Notwithstanding the increasing use of this technology the world over, it is not yet available in India. Lidar data have potential to be effective in many disaster management programmes, including the most frequently occurring floods in India[42]. However, this technology has the potential of conserving the precious forest resources and providing better understanding of management, which are difficult to comprehend otherwise, due to the limitations imposed by conventional and other data-collection techniques. Forest management strategy in India should be based on reliable, lidar-derived database on forest structure and its productive potential.

India is one of the important centres of biodiversity, having contributed 167 species of plants whose origin and diversity is in this country. Due to indiscriminate felling of trees, the forest area has been drastically shrinking. Lidar-derived information can be used for selective tree-felling and other forestry management issues in the country. Especially in north India, lidar may prove to be an effective forest-economy generation tool, and thus would improve the livelihood of the local inhabitants. Lidar has the potential to contribute towards the achievement of the objectives of the 'national forest policy' that aims at (i) ensuring environmental stability and ecological balance, including atmospheric equilibrium, which are vital for the sustenance of all life forms, human, animal and plant, (ii) deriving direct economic benefit, (iii) setting up a national goal to have a minimum of one-third of the total area of the country under forest or tree cover. In the hills and mountainous regions, lidar technology can help maintain two-third of the area under such cover in order to prevent erosion and land degradation, and to ensure the stability of the fragile eco-system. The Forest Survey of India (FSI), which presently uses satellite remote sensing data to achieve its objectives, i.e. (i) forest cover mapping, (ii) thematic mapping, (iii) inventory of forest/tree resources and data processing, (iv) training, (v) development of forest survey methodologies, (vi) special studies, and (vii) consultancy, can improve qualitatively by using lidar technology. The accuracy of density level forest stratification would be benefited from the use of lidar-based three-dimensional data set. Supplemented with IRS satellite data set, FSI can well improve its 'forest cover monitoring mandate' at a cycle of two years, thus providing information on policy making and planning for the existing deforestation, and increasing the green cover of the country. It is believed that this article would serve as a 'wake-up call' for foresters, planners, managers and researchers to utilize lidar technology for better management of the forest resources of the country.

1. Champion, H. G. and Seth, S. K., *A Revised Survey of Forest Types of India*, Manager of Publications, Government of India, New Delhi, 1968.
2. Wehr, A. and Lohr, U., *ISPRS J. Photogramm. Remote Sensing*, 1999, **54**, 68–82.
3. Lefsky, M. A., Cohen, W. B., Parker, G. G. and Harding, D. J., *BioScience*, 2002, **52**, 19–30.
4. Roy, P. S., Kaul, R. N., SharmaRoy, M. R. and Garbyal, S. S., *Int. J. Remote Sensing*, 1985, **6**, 411–418.
5. Young, M., *Optics and Lasers – Series in Optical Sciences*, Springer, Berlin, 1986, p. 145.
6. Baltsavias, E. P., *ISPRS J. Photogramm. Remote Sensing*, 1999, **54**, 164–198.
7. Kraus, K. and Pfeifer, N., *ibid*, 1998, **53**, 193–203.
8. Murakami, H., Nakagawa, K., Hasegawa, H., Shibata, T. and Iwanami. E., *ibid*, 1999, **54**, 148–152.
9. Winker, D. M., Couch, R. H. and McCormick, M. P., *IEEE*, 1996, **84**, 164–180.
10. Hogan, R. J., Illingworth, A. J., Poiares Baptista, J. P. V. and O'Conner, E. J., *Q. J. R. Meteorol. Soc.*, 2002, **128**, 1–15.
11. Behera, M. D., Dissertation, GDTA, University of Paris VI (submitted), 2002.
12. Dubayah, R. O. *et al.*, Proceedings of Lan Satellite Information in the Next Decade, II: Sources and Applications, American Society of Photogrammetry and Remote Sensing. Bethesda, MD, 1997, pp. 100–112.
13. Baltsavias, E. P., *ISPRS J. Photogramm. Remote Sensing*, 1999, **54**, 199–214.
14. Parker, G., Lefsky, M. A. and Harding. D. J., *Remote Sensing Environ.*, 2001, **76**, 298–309.

15. Nelson, R., Krabill, W. and Maclean, G., *ibid*, 1984, **15**, 201–212.
16. Nelson, R., Krabill, W. and Tonelli, J., *ibid*, 1988, **24**, 247–267.
17. Nelson. R., Oderwald, R. and Gregoire, G., *ibid*, 1997, **60**, 311–326.
18. Nilsson, M., *ibid*, 1996. **56**, 1–7.
19. Naesset, E., *ibid*, 1997, **61**, 246–253.
20. Lefsky, M. A., Harding, D. J., Cohen, W. B., Parker, G. G. and Shugart, H. H., *ibid*, 1999, **67**, 83–98.
21. Means, J. E. *et al*., *ibid*, 1999, **67**, 298–308.
22. Drake, J. B., Dubayah, R. O., Knox, R. G., Clark, D. B. and Blair, J. B., *ibid*, 2002, **81**, 378–392.
23. Lefsky, M. A., Cohen, W. B., Acker, S. A., Parker, G. G., Spies, T. A. and Harding, D. J., *ibid*, 1999, **70**, 339–361.
24. Magnussen, S. and Boudewyn, P., *Can. J. For. Res*., 1998, **28**, 1016–1031.
25. Means, J. E., Acker, S. A., Fitt, B. J., Renslow, M., Emerson, L. and Hendrix, C., *Photogramm. Eng. Remote Sensing*, 2000, **66**, 1367–1371.
26. Magnussen, S., Gougeon, F., Leckie, D. and Wulder, M., Remote Sensing and Forest Monitoring, Conference Proceedings, Rogow, Poland, 1999.
27. Nelson. R., *Remote Sensing Environ*., 1997, **60**, 327–334.
28. Naesset, E., *ISPRS J. Photogramm. Remote Sensing*, 1997, **52**, 49–56.
29. Weltz, M. A., Ritchie, J. C. and Fox, H. D., *Water Resour. Res*., 1994, **30**, 1311–1319.
30. Wulder, M., Olaf, N. K. and Goodenough, D. G., *Remote Sensing Environ*., 2000, **73**, 103–114.
31. Maclean, G. A. and Krabill, W. B., *Can. J. Remote Sensing*, 1986, **12**, 7–18.
32. Menenti, M. and Ritchie, J. C., *Water Resour. Res*., 1994, **30**, 1329–1337.
33. Andersen, H., Reutebuch, S. E. and Schreuder, G. F., Proceedings of the Twenty-third Annual Canadian Symposium on Remote Sensing, Quebec, QC, 20–24 August 2001.
34. Lillesand, T. and Kiefer, R., *Remote Sensing and Image Interpretation*, Wiley, New York, 2000, 4th edn.
35. Hyyppa, J., Pyysalo, U., Hyyppa, H. and Samberg, A., 20th EARSeL Symposium and Workshop, Dresden, Germany, 2000.
36. Saito, Y., Saito, R., Kawahara, T. D., Nomura, A. and Takeda, S., *For. Ecol. Manage*., 2000, **128**, 129–137.
37. Naesset, E., *Remote Sensing Environ*., 2002. **80**, 88–99.
38. Leckie, D., Gougeon, F., Quinn, R., Hill, D., Armstrong, L., Hiemstra, R. and Shreenan, R., Proceedings of the Twenty-third Annual Canadian Symposium on Remote Sensing, Quebec, QC, 20–24 August 2001.
39. Lim, K., Tretiz, P., Groot, A and St-Onge, B., *ibid*.
40. Weishampel, J. F., Ranson, K. J. and Harding, D. J., *Selbyana*, 1996, **17**, 6–14.
41. Blair, J. B., Rabine, D. L. and Hofton, M. A., *ISPRS J. Photogramm. Remote Sensing*, 1999, **54**, 115–122.
42. Lohani, B., Indian Society for Remote Sensing Symposium-2000, Kanpur.
43. Drake, J. B. *et al*., *Remote Sensing Environ*., 2002, **79**, 305–319.
44. Blair, J. B. and Hofton, M. A., *Geophys. Res. Lett*., 1999, **26**, 2509–2512.
45. Ritchie, J. C., Menenti, M. and Weltz, M. A., *Int. J. Remote Sensing*, 1996, **17**, 3705–3724.
46. Drake, J. B. and Weishampel, J. F., *Forest Ecol. Manage*., 2000, **128**, 121–127.

Received 28 August 2002; revised accepted 1 October 2002

Human–mangrove conflicts: The way out

V. P. Upadhyay, Rajiv Ranjan and J. S. Singh*

Mangrove resources are available in approximately 117 countries, covering an area of 190,000 to 240,000 km^2. *Countries like Indonesia, Nigeria and Australia have the largest mangrove areas. These ecosystems harbour 193 plant species, 397 fishes, 259 crabs, 256 molluscs, 450 insects and more than 250 other associated species. Mangrove ecosystem has the highest level of productivity among natural ecosystems, and performs several ecosystem services. The continued exploitation of mangroves worldwide has led to habitat loss, changes in species composition, loss of biodiversity and shifts in dominance and survival ability. Worldwide, about half of the mangroves have been destroyed. The Indian mangrove biodiversity is rather high. The increase in the biotic pressure on mangroves in India has been mainly due to land use changes and on account of multiple uses such as for fodder, fuel wood, fibre, timber, alcohol, paper, charcoal and medicine. Along the west coast alone, almost 40% of the mangrove area has been converted to agriculture and urban development. Our understanding of the natural processes in this vulnerable and fragile ecosystem is far from adequate. Environmental awareness, proper management plan and greater thrust on ecological research on mangrove ecosystems may help save and restore these unique ecosystems.*

MANGROVE ecosystems are open systems which exchange matter and energy with adjacent marine, freshwater and terrestrial ecosystems. The extent of wave and tidal coping between mangrove and offshore marine biotopes controls the intensity of interaction between the systems[1]. These ecosystems are effective in storing large amounts of inorganic and organic nutrients which are washed into mangroves from the rivers and continental drainage. They also process huge amounts of organic matter, dissolved nutrients, pesticides and other pollutants which

V. P. Upadhyay is in the Eastern Regional Office, Ministry of Environment and Forests, Bhubaneswar 751 023, India; Rajiv Ranjan is in the Forest Department, Dharwad, India; J. S. Singh is in the Department of Botany, Banaras Hindu University, Varanasi 221 005, India.
*For correspondence. (e-mail: vpupadhyay@hotmail.com)