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The Laser Vegetation Imaging Sensor: a medium-altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography

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Abstract

The Laser Vegetation Imaging Sensor (LVIS) is an airborne, scanning laser altimeter, designed and developed at NASA's Goddard Space Flight Center (GSFC). LVIS operates at altitudes up to 10 km above ground, and is capable of producing a data swath up to 1000 m wide nominally with 25-m wide footprints. The entire time history of the outgoing and return pulses is digitised, allowing unambiguous determination of range and return pulse structure. Combined with aircraft position and attitude knowledge, this instrument produces topographic maps with dm accuracy and vertical height and structure measurements of vegetation. The laser transmitter is a diode-pumped Nd:YAG oscillator producing 1064 nm, 10 ns, 5 mJ pulses at repetition rates up to 500 Hz. LVIS has recently demonstrated its ability to determine topography (including sub-canopy) and vegetation height and structure on flight missions to various forested regions in the US and Central America. The LVIS system is the airborne simulator for the Vegetation Canopy Lidar (VCL) mission (a NASA Earth remote sensing satellite due for launch in year 2000), providing simulated data sets and a platform for instrument proof-of-concept studies. The topography maps and return waveforms produced by LVIS provide Earth scientists with a unique data set allowing studies of topography, hydrology, and vegetation with unmatched accuracy and coverage.

Keywords: laser altimetry; vegetation height; topography; lidar

1. Introduction

Laser altimetry is an emerging remote sensing technique with a wide variety of applications in the Earth and planetary sciences. Although the technique has existed since the early 1970s (for example, laser altimeters were flown on the Apollo 15, 16 and 17 missions to the Moon (Kaula et al., 1974)), only in the last decade have significant technological advances resulted in the development of several reliable and accurate spaceborne sensors. These include the Shuttle Laser Altimeter (SLA) (Garvin et al., 1998) and the Mars Observer Laser Altimeter (MOLA) (Smith et al., 1998), which have made unique and significant measurements of the topography of Earth and Mars. The development of these instruments, along with that of future spaceborne instruments such as the Vegetation Canopy Lidar

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(VCL) (Bufton and Blair, 1996; Dubayah et al., 1997) and the Geoscience Laser Altimeter System (GLAS) at NASA's Goddard Space Flight Center (GSFC), has driven the need to develop prototype laser altimeters for testing and measurement concept validation from aircraft platforms.

A series of airborne laser altimeters have supported the development of instrument and data processing techniques as well as new science applications for laser altimetry. These systems include the Airborne Topographic Laser Altimeter System (ATLAS) (Bufton et al., 1991) and the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) (Blair et al., 1994). Instrumentation has evolved from low-altitude (500 m above ground level (AGL)), small-footprint, range-only systems to medium altitude (5–10 km AGL), large-footprint, scanning systems that utilise return pulse digitisation to characterise the vegetation structure within the footprint. The technique of scanning 10–30 m footprints (Fig. 1) and using waveform analysis to accurately derive surface topography, and vegetation height and structure over wide areas was brought to its current level of maturity using SLICER and Laser Vegetation Imaging Sensor (LVIS), and is the basis for the VCL mission measurement concept. LVIS will provide the test-bed and data sets for algorithm development, instrument design and performance assessment, and the calibration and validation of the VCL mission.

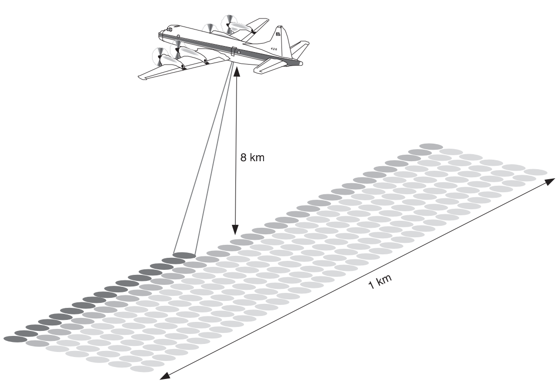

Fig. 1. A flight configuration of the LVIS airborne laser altimeter. A 1-km wide swath is generated using forty 25-m wide footprints from 8 km AGL. Smaller footprint sizes are possible, as are overlapping footprints or less dense sampling schemes.

2. The Laser Vegetation Imaging Sensor

2.1. System overview

LVIS is a pulsed laser altimeter and measures range by timing a short (< 10 ns duration) pulse of laser light between the instrument and the target surface. The entire time history of the outgoing and return laser pulses is digitised using a single detector, digitiser and timing clock, and unambiguously describes the range to the surface as well as the vertical distribution of surfaces within each laser footprint. The LVIS system operates at altitudes up to 10 km AGL and has a 7° potential field-of-view (PFOV) within which footprints can be randomly spaced across track (Fig. 1). Scanning is performed using galvanometer-driven scan mirrors that control the pointing of both the laser and the telescope instantaneous field-of-view (FOV). Scan mirrors are positioned in a stepped pattern, stopping to fire the laser and integrate the return signal at each beam location. This raster scan pattern efficiently covers 100% of the area within the data swath. Footprint sizes from 1 to 80 m are possible, determined by the AGL altitude of the airplane and the focal length of a diverging lens in the output path.

2.2. System design

The design goals for LVIS include: wide swath, high-altitude capability, variable sampling pattern and footprint diameter, outgoing and return pulse digitisation, accurate ranging, and automated real-time ground finding/tracking (even in the presence of clouds, atmospheric haze, and significant topographic relief). To achieve the wide data swath using a large aperture telescope and small, high-bandwidth, silicon avalanche photodiode (Si:APD) detectors, the telescope FOV is mechanically scanned across the detector face using a lightweight, galvanometer-driven mirror. Accurate ranging with large footprints requires waveform digitisation of the return pulse to allow compensation for pulse distortion introduced by interaction with complex surfaces. Previous airborne and spaceborne altimeter systems utilised a separate time interval unit (TIU) and waveform digitiser to determine range to the surface and the shape

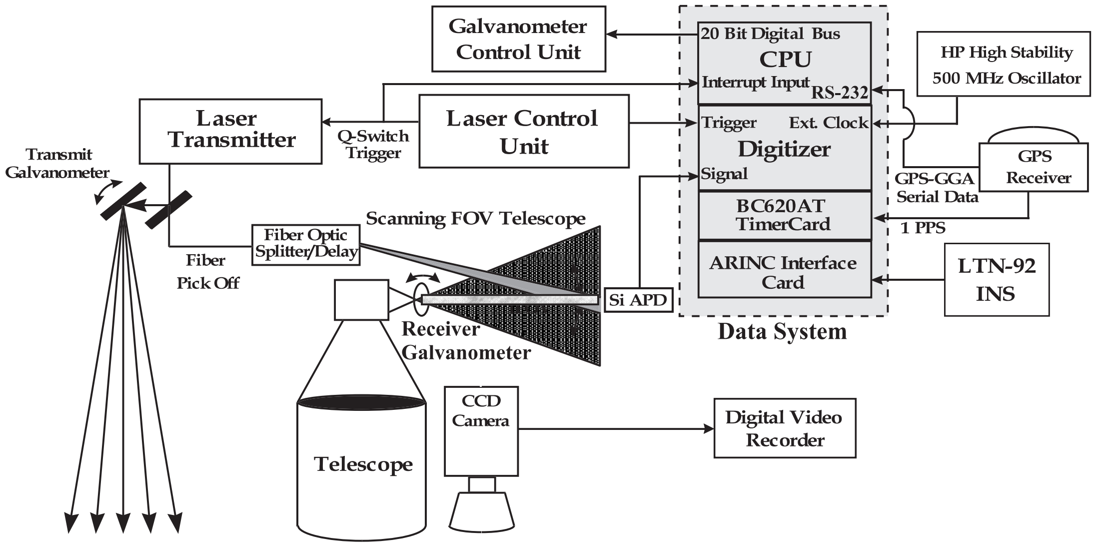

Fig. 2. Block diagram showing the LVIS sensor design. Sub-systems include the laser, telescope, receiver system, real-time data system, high stability frequency oscillator, Litton LTN-92 INS, GPS receiver, and CCD camera and digital video recorder.

of the return pulse. The TIU timing cannot be related to the waveform more precisely than a single waveform time bin because the TIU and the digitiser utilise separate, asynchronous clocks. The digitiser-only scheme employed in LVIS eliminates any ambiguity between the timing and waveform recording functions allowing precise determination of pulse location ($< 1/10$ digitiser bin).

Fig. 2 shows a high-level block diagram of the LVIS sensor design. Table 1 summarises the design parameters of the LVIS system. The system is composed of several sub-systems, all mounted on a 60-cm square, 1.9-cm thick aluminum plate.

2.2.1. Optical system

The receiver system consists of a 200-mm diameter, 5-power telescope with a 25-mm exit pupil. The telescope has a 200-mm aperture, $f/2$ Petzval [1] objective with a 400-mm focal length directing light through a 50-mm focal length $f/1.8$ eyepiece, which produces a 25-mm collimated beam. A scan mirror, located at the exit pupil of the telescope, directs the beam through a 10-nm bandpass filter and onto a 25-mm molded aspheric condenser lens which focuses onto the 0.8-mm Si:APD detector. The scan mirror is a 25×40 mm beryllium mirror that was custom designed to be lightweight for fast scanning, yet stiff enough to remain flat during and just after the intense acceleration of scanning. The receiver box can accommodate two more detectors, enabling

[1] Petzval lens: a high speed, narrow FOV lens composed of two achromatic lenses positioned about an aperture stop; named after the Austrian optician Josef Petzvald.

Table 1
System characteristics of the LVIS altimeter

Telescope aperture	20 cm
Telescope total FOV	110 mrad
Detector FOV	8 mrad
Detector band width	90 MHz
Bandpass filter band width	10 nm
Digitiser sampling rate	500 Msamp/s
Digitiser effective bits	7
Laser output energy	5 mJ
Laser pulse width	10 ns (FWHM[a])
Laser spatial energy pattern	TEM00 (single mode)
Pulse repetition rate (rep-rate)	100–500 Hz
Laser output wavelength	1064 nm
Data rate (at 300 Hz rep-rate)	150 kbytes/s
Swath width (at 8 km altitude)	0.9 km
Footprint diameter	1–80 m
Maximum operating altitude	> 10 km

[a] Full width at half maximum.

the simultaneous collection of dual-wavelength, dual-polarisation data.

2.2.2. Laser

The transmitter is a water-cooled, solid-state, diode-pumped, Nd:YAG oscillator-only laser, designed and manufactured by Cutting Edge Optronics (St. Louis, MO). The laser cavity is housed in a hermetically sealed aluminum enclosure that measures $45 \times 13 \times 13$ cm. Operating at rates of up to 500 Hz, the laser emits 5 mJ, 10 ns, Gaussian-shaped (temporally and spatially) optical pulses at a wavelength of 1064 nm. Accurate ranging to a mean elevation in a wide laser footprint can be confounded by a complex spatial energy distribution across the laser spot, thus, the laser transmitter was required to have a single-spatial mode (TEM00) energy pattern. A fiber-coupling lens is placed behind the final turning mirror inside the laser enclosure to capture a small amount ($< 1\%$) of the laser output and direct it through two optical fibers (start pulse and calibration pulse with 100 m (300 ns) delay). The laser output beam is directed through the output scanner box containing filter wheels to control the output power to optimise return signal strength, a diverging lens to control the size of the footprint on the surface, a lockable pitch control for boresighting, and the galvanometer-driven output scan mirror.

2.2.3. Altimetry and waveform analysis electronics

The digitiser-only altimetry electronics scheme is a unique feature of the LVIS instrument; all of the pulse discrimination, ranging, range gating, and transmit and receive pulse shape recording are performed using a single detector, digitiser (Signatec, Corona, CA), and oscillator (HP model 8657B). The entire time history of the detector output is recorded at 500 Msamp/s with 8 bit resolution from before the laser is fired until beyond any possible surface returns. Noise statistics (mean and standard deviation) for generating pulse finding criteria are calculated for each shot from a section of time/memory that is beyond any possible surface return, thus ensuring that it is signal-free. The digitiser, triggered by the laser Q-switch pulse, begins digitising slightly before the output pulse and continues for 120 μs (~ 20 km in range). A real-time ground finding algorithm (Fig. 3) searches a 2-km window that is

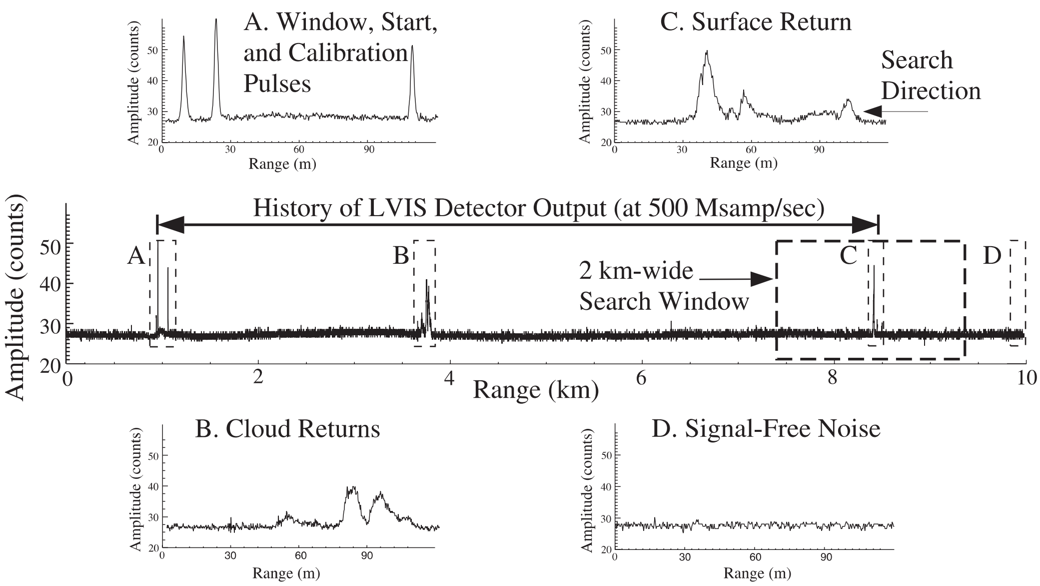

Fig. 3. The LVIS real-time ground finding algorithm. Central figure shows an amplitude vs. range plot of the detector output. The 2-km window in the digitiser record is searched from the back to locate the surface return. (a) Window return, start pulse, and fiber calibration pulse. (b) Returns from an optically opaque cloud layer between the aircraft and the ground. (c) Vegetated surface return. Left-most signal is from vegetation, right-most pulse is the sub-canopy ground return. (d) Digitised noise used to calculate noise statistics for the search algorithm.

automatically centred on a valid ground location from a previous shot. The search routine returns the location of the first signal detected searching from the back of the window; thus, ground returns are found before cloud returns eliminating the need for range gating.

2.2.4. Real-time data system

The real-time data system consists of a Pentium-based ISA/PCI motherboard operating under MS-DOS. The interrupt-driven, real-time control software was written using Borland C. The main tasks performed by the data system are: to collect the outgoing and return waveforms from the digitiser, display range and waveform data for real-time evaluation of instrument performance, time-stamp all samples, and store binary data. The data system also controls scan mirror positioning, the ground-finding algorithm, the ground-following algorithm, and digital interfaces to Global Positioning System (GPS) and Litton LTN-92 Inertial Navigation System (INS) systems. A timer card (Datum BC620AT), synchronised to the on-board GPS 1PPS, provides accurate time-stamping. INS attitude data is collected through an ARINC-429 interface card. A digital I/O interface is used to communicate with the galvanometer controller. A SCSI disk drive is used to store the LVIS data. The real-time data rate that LVIS produces (during nominal 300 Hz operation) is 150 kbytes/s. An LVIS data record contains a transmit-pulse waveform, receive-pulse waveform, range between waveforms, noise statistics, GPS time tag, INS attitude, and scan angle.

The INS system provides platform roll, pitch, and bearing information at a 64-Hz sampling rate with 0.0055 degree resolution. Two GPS (Ashtech Z-XII) receivers provide real-time position which is fed into a pilot assist system that allows precision flying (to within 100 m) along predetermined flight tracks (Wright and Swift, 1996). Data from the on-board GPS are processed post-flight with data from ground-based, static GPS receivers to provide an airplane trajectory with vertical accuracy of ~10 cm (Krabill et al., 1995).

3. Operations

To date, the LVIS instrument has flown on two aircraft based at NASA's Wallops Island Flight Facility (WFF); the T-39 Sabre-Liner, a small, twin engine business class turbo jet, and the C-130 Hercules, a four-engine turbo-prop cargo and surveillance aircraft. Both aircraft have a nadir-viewing 0.4 m diameter quartz window.

Bore sighting and alignment of the scan mirrors is done upon initial installation, and checked before

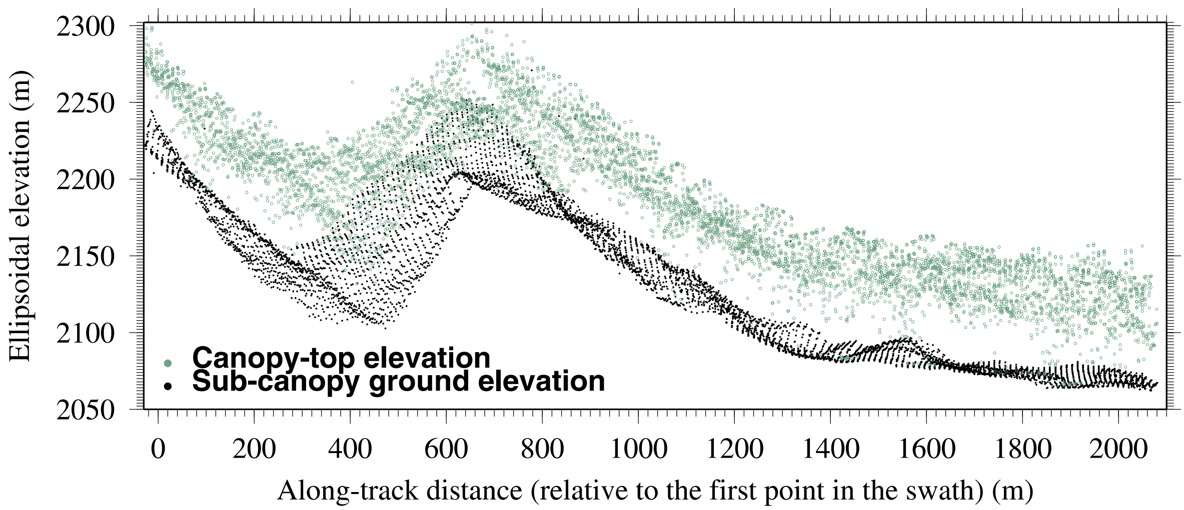

Fig. 4. Sub-canopy and canopy-top elevations along a ~2-km long data line in the Sequoia National Forest, CA, collected in October 1997. Each footprint yielded both canopy top (green dots) and sub-canopy topography (black dots).

each flight. Return energy and peak for each beam is graphically displayed enabling the operator to align the system in real-time. Once alignment is complete, a series of aircraft roll and pitch manoeuvres allow determination of angle and time biases. The operator monitors return signal strength and adjusts filter wheels to control transmit power. The flight plan is pre-programmed into the GPS display computer for the pilots. All altimetry data are transferred to 8 mm Exabyte tape at mission end.

Geolocation of each laser shot during post-processing produces latitude, longitude, mean ground elevation, and relative heights of surfaces within each footprint (e.g., tree height). A detailed description of the processing procedures can be found in the work of Hofton et al. (1999). This includes the combination of the laser range data with GPS position and INS pointing information at the epoch of each laser shot and performing a series of transformations to rotate and translate the laser range from a local, aircraft reference system to a global reference system such as WGS-84.

4. Recent missions

LVIS has recently demonstrated its ability to acquire 1000-m wide data swaths from a medium-altitude aircraft. These data are used to produce accurate topographic maps, and investigate vegetation height and vertical structure within each laser altimeter footprint. The first deployment of the LVIS system took place in October 1997, and included a test flight over the Sequoia National Forest in southeast California. LVIS was flown in the T-39 jet aircraft at 6 km AGL operating at 400 Hz. A total of 35 across-track footprints were generated, 25 m in diameter, and separated by ~10 m both across and along-track. Results from this campaign are shown in Fig. 4. Greater than 99% of the laser shots yielded both canopy-top and sub-canopy elevation data. The sub-canopy topography is self-consistent, but note the large height variations in the canopy-top measurement, not an unexpected result considering the maturity of this forest.

A mapping flight over the Patuxent and Patapsco Rivers in Maryland was also performed in October 1997. LVIS was flown in the T-39 aircraft at ~7 km AGL. The laser operated at 230 Hz, producing 25-m wide footprints, separated by ~20 m both along and across track. Five flight lines were flown over the targets, each offset from the previous one by 500 m across track. In total, ~2.5-km wide swaths of land along each of the rivers were mapped. Topography and vertical extent maps from the Patapsco River region are shown in Fig. 5. The topography map (Fig. 5a) includes bare-ground as well as sub-

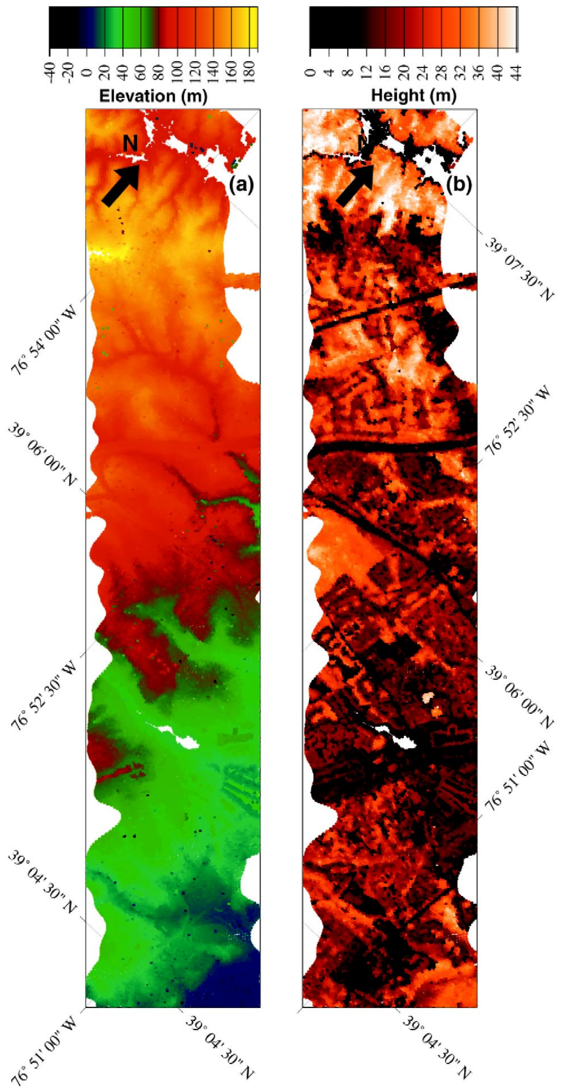

Fig. 5. (a) Ground topography and (b) height within each footprint in the Patapsco River region, MD, determined using LVIS in October 1997. Laser footprints are spaced ~20 m apart, with increased density in regions of swath overlap.

canopy elevations and exhibits excellent consistency between adjacent footprints. The vertical extent map (Fig. 5b) corresponds to the heights of the highest reflecting surface within each footprint. Several roads and building developments are apparent, as well as forested areas.

In March 1998, as part of the calibration and validation activities for the VCL mission, LVIS mapped the area surrounding the La Selva Biological Research Station in the Atlantic lowlands of Costa Rica to determine tree heights and sub-canopy topography in mature rainforests. The laser operated at 320 Hz, producing eighty 25-m wide footprints, spaced ~9 m apart across track and 27 m apart along track from 8 km AGL. A 5000-m wide swath of land was mapped using seven passes over the region. Each pass was offset from the previous one by ~700 m. Preliminary analysis shows that 90% or more of the returns penetrated the dense tropical moist forest to a level consistent with adjacent footprints.

5. Summary and discussion

The LVIS has demonstrated its ability to determine surface topography (including sub-canopy) as well as vegetation height and structure. The system is capable of operating up to 10 km AGL, generating a 1000-m wide swath of data using a nominal footprint size of 25 m. The sensor has many advantages over past airborne systems, most importantly, its digitiser-only altimetry electronics scheme performs all ranging, range-gating, pulse discrimination, and waveform digitisation functions using a single detector and oscillator. Recent missions in US and Central America, have established LVIS as an important instrument for determining vegetation height and structure, and sub-canopy topography.

The concept of active, direct measurement of vegetation height and structure as well as ground topography (including sub-canopy) using waveform digitisation of 10–30 m footprints is the basis for the VCL mission due to launch in mid 2000. LVIS is currently operational as the airborne simulator for VCL and is the airborne test-bed for VCL ground-tracking algorithms and instrument performance analysis. We utilise this existing, experimental sensor to acquire data sets from an airborne platform to demonstrate and validate new instrument concepts at various stages in their development process. Topographic imaging at the levels of vertical accuracy possible with LVIS open up new scientific opportunities for investigating previously ‘un-measurable’ aspects of the very local scale and often dynamic landscapes of Earth, including the vertical character of vegetation. LVIS’ unique capability for measuring the sub-meter topography beneath forest canopies could facilitate improved hydrologic modelling at the individual drainage basin level in areas that have traditionally escaped adequate treatment. The hydrological properties of the flanks of heavily vegetated volcanoes in the tropics are woefully uncertain, yet these regions are those that control the propagation of catastrophic debris and mudflow. Furthermore, the relatively wide swath spatial coverage provide the basis for monitoring the sub-meter topography before and after major catastrophic events, such as those associated with ‘natural hazard events’ including gigantic floods and volcanic eruptions.

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