

Airborne Lidar Simulator for the Lidar Surface Topography (LIST) Mission

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ABSTRACT

In 2007, the National Research Council (NRC) completed its first decadal survey for Earth science at the request of NASA, NOAA, and USGS.[1] The Lidar Surface Topography (LIST) mission is one of fifteen missions recommended by NRC, whose primary objectives are to map global topography and vegetation structure at 5 m spatial resolution, and to acquire global surface height mapping within a few years. NASA Goddard conducted an initial mission concept study for the LIST mission in 2007, and developed the initial measurement requirements for the mission.

1. INTRODUCTION

In the Decadal Survey, the NRC recommended a total of fifteen missions with benefits ranging from information for short-term needs, such as weather forecasts and warnings for protection of life and property, to the longer-term scientific understanding necessary for future applications that will benefit society in ways still to be realized. Most future topographic mapping missions will likely utilize multiple laser beams in the cross track orientation to facilitate surface slope measurements and reduce the time needed to globally map surface topography. The most ambitious is a NRC recommended tier-3 mission named Lidar Surface Topography (LIST). In this paper, we will discuss our effort in developing measurement techniques and technologies for the LIST mission.

2. LIST MISSION

The key attributes of the LIST mission, as described in the NRC Earth Science Decadal Survey report, are: (1) a medium cost mission to be launched by NASA between 2016-2020; (2) a single-instrument payload carrying an imaging lidar at low Earth orbit; (3) one-time global mapping of land, ice sheet and glacier topography and vegetation structure through the duration of the mission; (4) observe topography and vegetation structure change through time in selected

areas; and (5) achieve 5 m horizontal resolution, 0.1 m vertical precision, and decimeter-level absolute vertical accuracy for ground surface topography including where covered by vegetation.

The measurement requirements for the mission were developed in an advanced mission concept study for LIST, which was carried out by NASA Goddard in mid-2007. The LIST Science Working Group (SWG) report defined the traceability linking science objectives and measurement requirements for land topography, vegetation structure, ice sheets and glaciers, and inland water bodies. The results of the study highlighted the key challenges for any lidar approach. The lidar must be capable of: (1) mapping a swath with a width of at least 5 km to acquire global coverage in a reasonable amount of time; (2) ranging accurately to the surface through thin to moderate cloud cover in order to acquire complete coverage in regions that are frequently cloudy; (3) operate with solar background noise to accomplish mapping during both day and night conditions (even for a dawn-dusk sun-synchronous orbit the solar zenith angle is large during parts of the year); (4) large dynamic range to accommodate highly varying apparent reflectance conditions due to changes in surface reflectance, atmospheric transmission and canopy cover; (5) high sensitivity in order to detect returns from the ground through dense vegetation cover; (6) an effective pulse rates of 10 kHz or less to allow atmospheric profiling and unambiguous surface ranging through clouds; and most importantly (7) highest efficiency in order to minimize required power, mass, size and cost.

3. LIST TECHNOLOGY DEVELOPMENT

In 2009 we started a three-year Instrument Incubator Program (IIP) project, funded by NASA's Earth Science Technology Office (ESTO), for definition and early technology development for LIST. The purpose is to develop and demonstrate the techniques and technologies for a next-generation, efficient, swath-mapping space laser altimeters.

The instrument requirements associated with the LIST science objectives far exceed those of existing space-laser-altimeter technologies. A viable LIST instrument needs to be able to generate a swath width of 5 km, image this swath onto a detector array and produce an image that describes the topography of the sampled area, including through foliage if covered by vegetation, and the 3-D structure of the vegetation cover. Our pushbroom photon counting approach has much higher performance and efficiency than recent single-beam scanning laser altimetry systems and leverages investments by various technology sectors internationally.

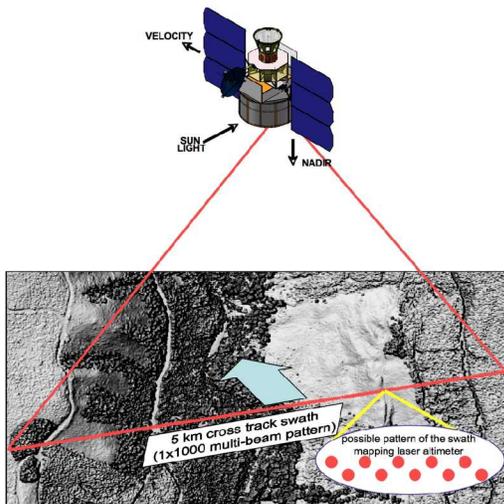


Figure 1. Concept drawing of the LIST satellite generating a 5 km swath containing 1000 beam spots at 5 m per spot.

The instrument concept for LIST is shown in **Figure 1**. A swath 5 km wide composed of 1000 laser beams in a linear array is oriented in the cross-track direction. The divergence of each beam yields 5-meter diameter footprint on the ground from a 400 to 425 km orbit altitude that are contiguous cross-track. **Figure 2** shows conceptually the echo pulse structure with information containing the canopy and foliage structure as well as the ground return. As seen in **Figure 1**, the ground pattern of the illuminated spots is arranged in a staggered fashion to mitigate any crosstalk from atmospheric scatter from adjacent spots at the detector array. In this configuration, each pixel on the detector array can have a larger field of view (FOV) than the illuminated spot to aid alignment while eliminating crosstalk from adjacent channels. At 10 kHz laser repetition rate and a nominal spacecraft ground velocity of 7 km/sec in low Earth orbit, laser footprints are spaced 0.7 m along track yielding 7 pulses per 5 m pixel. This over-sampling along track enables a sufficient density of detected ground returns under adverse observing conditions (low atmospheric

transmission due to thin clouds and/or aerosols and ground obscuration by vegetation cover). Our measurement approach differs from the traditional single pulse lidar altimeters in which laser pulses on order of ten's millijoules at relatively low repetition rate are used. We use a micropulse photon counting, approach with a ~ 10 kHz pulse rate laser, shorter pulse width (as shown conceptually in **Figure 2**) to accumulate a few hundred photons from each 5 m pixel for information processing.

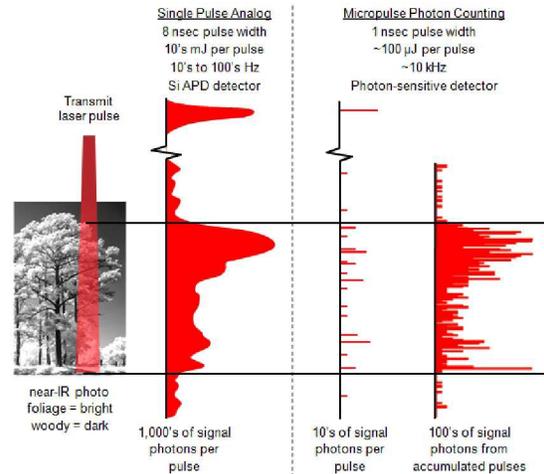


Figure 2. Approaches for measuring the time-of-flight information of laser echo pulses into vegetation structure heights and ground return.

4. LIST INSTRUMENT INCUBATOR PROGRAM (IIP)

In 2009 we began a three-year program on technology development for LIST. Our approach will ultimately allow for simultaneous measurements of 5-m spatial resolution topography and vegetation vertical structure with decimeter vertical precision in an elevation-imaging swath several km wide from a 400 km altitude Earth orbit. Our IIP objective is to demonstrate the measurement technique and key technologies for a highly efficient surface lidar to meet the goals of the LIST mission.

During the first two years, we are concentrating our work in developing some critical subsystems (laser, detector, optics and receiver processing systems) in preparation for an airborne demonstration of a multi-beam swath mapping altimeter system in the final year of the IIP. Our ultimate goal is to develop a $>15\%$ wall plug efficient laser system coupled with a highly sensitive multi-element detector for the space mission.

4.1. LASER TRANSMITTER

For LIST a swath of 5 km can be generated using 1000 beams each having 5 m footprint. Our goal of this work is to show a viable efficient path for generating the 1000 laser and photo-detector channels. According to our analysis, with the current photon counting detector sensitivity, the energy requirement per channel is ~ 100 μJ at 10 kHz with ~ 1 nsec pulse widths. To meet this, we are pursuing a master oscillator power amplifier (MOPA) laser architecture. Assuming that we need 10 MOPA lasers, each laser then subdivide to generate 100 beams will produce a 1000 beam swath. Thus each MOPA laser will need to deliver an energy of >100 mJ. At 10 kHz pulse rate, the average optical power is >100 Watt per laser. If the lasers have wall-plug efficiencies of $>15\%$, the prime power for the LIST lasers will be manageable with <7 kW of prime power from the spacecraft. During the first two years of the IIP we are developing a MOPA laser that will demonstrate the wall plug efficiency and necessary attributes to meet the measurement requirements. The final product will be able to generate 16 beams each having 100 μJ pulse energy.

4.2. RECEIVER

Another critical technology for LIST is high-sensitivity low-noise detectors that provide single-photon sensitivity. The backscatter laser signals by surface and biomass (e.g. grass, trees, etc.) at the satellite altitude are very weak. Detectors with high quantum efficiency (QE) and internal gain are needed to overcome detector amplifier noise and achieve the required signal-to-noise ratios. We are exploring a near single-photon sensitive detector array operating in analog mode, with $>1\text{GHz}$ bandwidth. We are currently working with several vendors to develop high bandwidth multi-element photon-sensitive detectors during the first two-year of the program. Candidate detectors for our prototype lidar include HgCdTe on CdZnTe APDs, impact-ionization-engineered InAlAs APDs [2] and multi-element anode InGaAsP intensified photodiode detectors (IPDs) [3].

4.3. OPTICAL SYSTEM

The airborne lidar will demonstrate a 16-beam version of the LIST space lidar. The sixteen beams orient in a 4×4 grid pattern with uniform spacing between spots. The overall dimension of the grid is $75\text{ m} \times 75\text{ m}$ ($7.5\text{ mrad} \times 7.5\text{ mrad}$) with 20 m (2 mrad) between spots. The grid will have a $14.5^\circ \pm 1^\circ$ clocking with respect to the aircraft velocity vector to yield an effective 5 m spot cross-track spacing as shown in **Figure 3**. A diffractive optical element (DOE) will be used to divide a single beam into 16 beams. A similar DOE is being used presently on the Lunar Orbiter Laser

Altimeter (LOLA) instrument on the Lunar Reconnaissance Orbiter (LRO). [4]

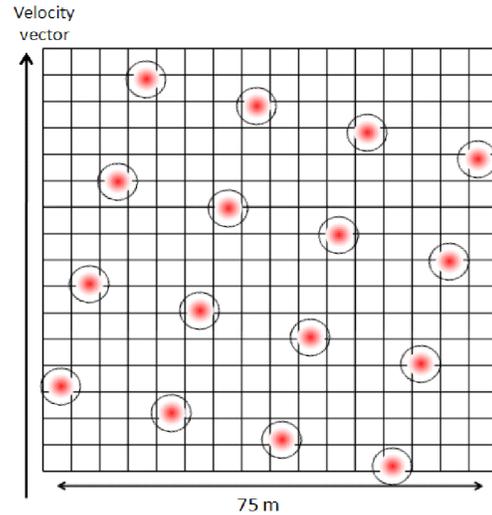


Figure 3. This figure illustrates the baseline footprint configuration of the IIP airborne lidar from 10 km altitude. The solid circles are the 5 m laser footprints with the open circles showing the detector field of view of ~ 7 m.

4.4. AIRBORNE DEMONSTRATION

In the 3rd year of work, we plan airborne demonstrations of the swath-mapping concept. We will leverage our recent experience on a micropulse lidar airplane demonstration.[5] Previously we demonstrated a lidar with a $1\text{ }\mu\text{J}$ per beam, a 10 KHz laser, and a single-photon-threshold detector (Geiger-mode APD) based receiver. Our new lidar using micropulse photon-counting approach will demonstrate a laser with $100\text{ }\mu\text{J}$ per beam, a 10 kHz pulse rate, and a receiver using single-photon-sensitive analog-mode detector and waveform-digitizer.

Our plan is to operate the instrument at a 10 km altitude. We intend to scale the receive telescope on this airborne experiment to the LIST mission concept. The LIST concept presently uses a 2-m receiver telescope at an orbit height of 400 km. From a 10 km airplane at altitude, a receive telescope diameter of 5 cm will provide the same detected signal. Table 1 shows a comparison between the airborne instrument being developed under this IIP and the LIST spaceborne instrument requirements. A number of flight tests over different regions are being considered. Candidate regions for the tests will be selected to demonstrate measurement concept that satisfy the LIST science objectives of mapping in cryosphere, water cycle, vegetation structure and solid Earth application areas.

Table 1. Comparison of Space- and Air-borne instruments for LIST.

LIST Objectives	Spaceborne Instrument	Airborne Instrument	Comments
Spatial Resolution	5 meter	5 meter	Use the same footprint, rather than scaled by angular divergence
Altitude	400 km	10 km	Scale: 40X
Swath Width	5 km (1000 beams)	80 m (16 beams)	Scale: 62.5X
Detection Scheme	Analog Photon Counting	Analog Photon Counting	Backup Option – Geiger Mode Photon Counting on Airborne Instrument
Telescope Size	2-meter Diffraction Limited telescope	0.127-meter Diffraction Limited telescope	Scaled by Altitude – 1/40X with margin
Laser Energy	100 μ J per beam for 1000 beam @ 10 kHz – 1 kW optical power or 6.7kW prime power assuming 15% efficiency	100 μ J per beam for 16 beam @ 10 kHz – 16 W optical power or 110 W prime power	Demonstration of full energy per beam meeting LIST's spaceborne instrument requirement
Detector	1000 pixels with > 1 GHz bandwidth on each pixel	16 pixels with > 1 GHz bandwidth on each pixel	Demonstrate the necessary bandwidth in multiple pixel detector array with photon counting sensitivity and waveform digitizing
Platform Speed	7000 m/sec	200 m/sec	Scale: 35X
Number of samples per footprint	7	250	During the Airborne campaign, we can sample every 35 th one to simulate space environment
Footprint Separation	0.7 meter	0.02 meter	Airborne will oversample by 35X
Beam dividing network	One scenario is to have 10 lasers, each with 1x100 beam divider diffractive optical element (DOE)	Single beam divides into 16 beams using a DOE	Demonstrate efficiency beam division technique using DOE
Spectral Linewidth	< 20 pm	< 20 pm	Demonstrate the technical approach to stabilize laser wavelength and spectral width when use with narrow receiver filter

5. CONCLUSIONS

In this work we are developing the measurement approach and lidar technologies for the LIST lidar mission requirements. The objectives are to mitigate the major risks and developing measurement techniques for the LIST mission. Our plans are to incorporate the work on the measurement approach and lidar technologies developed during the first two years into an airborne lidar simulator, and to demonstrate measurements in 2011.

6. ACKNOWLEDGMENT

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