Airborne Instrument 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 coverage with a few years. NASA Goddard conducted an initial mission concept study for the LIST mission 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 range 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 technologies and measurement techniques 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.

An advanced mission concept study for LIST, requested by NASA Science Mission Directorate and conducted internally at GSFC in mid-2007, detailed measurement requirements for the mission. The LIST Science Working Group (SWG) defined traceability matrices linking science objectives and measurement requirements for land topography, vegetation structure, ice sheets and glaciers, and inland water bodies. The results of the study highlight key challenges that are driving factors for any laser altimeter instrument approach used to achieve the mission objectives. The instrument 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 for atmospheric profiling and unambiguous surface ranging through clouds; and most importantly (7) highest efficiency in order to minimize required power, mass, size, complexity 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 early technology development for LIST. The purpose is to develop and demonstrate 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 new approach has much higher performance and efficiency than recent single-beam scanning laser altimetry systems and leverages investments by various technology sectors internationally.

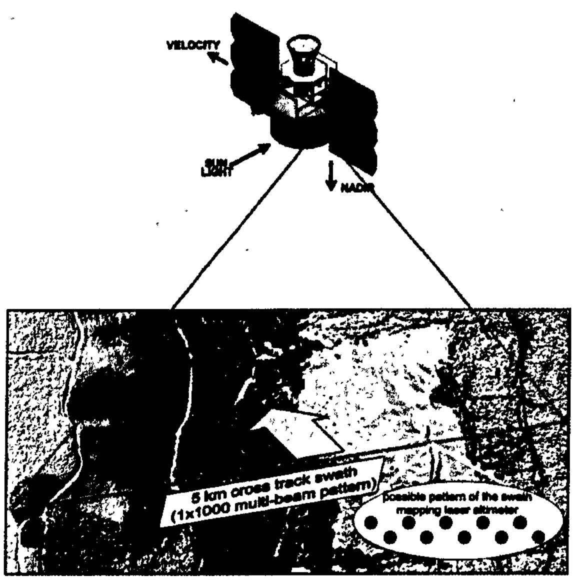

Figure 1. Concept drawing of the LIST satellite generating a 5 km swath containing 1000 beam spots at 5 m per spot.

A system level block diagram of 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 return 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 this staggered fashion to mitigate any crosstalk 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 eliminate 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).

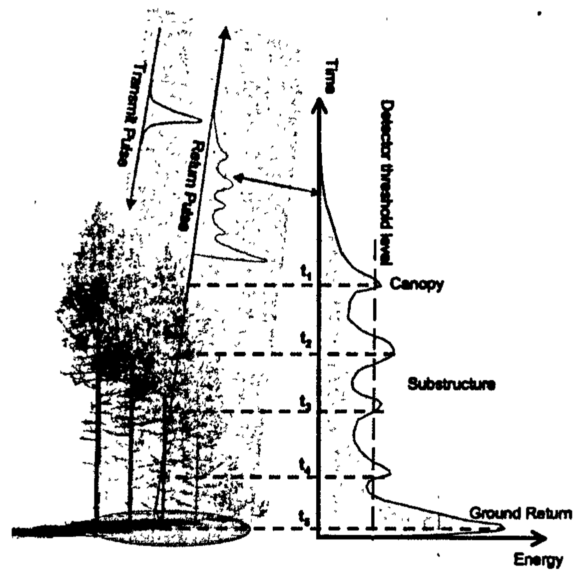

Figure 2. This figure illustrates the concept of interpreting time-of-flight information of a return pulse into vegetation structure heights and ground return.

4. LIST INSTRUMENT INCUBATOR PROGRAM (IIP)

In 2009 we began a three-year IIP effort on technology development for LIST. Our approach ultimately allows 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 to meet the goals of the LIST mission. Our IIP objective is to develop a highly efficient laser altimeter system that can be housed in a compact instrument providing data products that vastly exceed other instruments in the same class.

The ultimate goal of a >15% wall plug efficient laser system coupled with a highly sensitive multi-element detector is essential to realizing the ambitious global elevation mapping goals of the LIST mission. During the first two years of the IIP, we are concentrating our effort in developing all the critical subsystems (laser, detector, optical and data systems) in preparation for an airborne demonstration of a multi-beam swath mapping altimeter system in the final year of the IIP.

4.1. LASER TRANSMITTER

One of the goals of our IIP is to show the path for realization of a system capable of efficiently generating a 1000 laser and photo-detector channels. To fulfill LIST measurement requirements from space, a swath of 5 km can be generated using 1000 beams each having 5 m footprint. According to our link analysis, with the current photon counting detector sensitivity, the energy requirement per channel is ~100 μJ at 10 kHz and ~ 1 ns pulse width. To meet this, the most likely laser architecture is the master oscillator power amplifier (MOPA) approach. 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 >10 mJ and at 10 kHz, the average optical power is >100 Watt per laser. Lasers having wall-plug efficiencies of >15%, will make the prime power for LIST 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 of pulse energy.

4.2. RECEIVER

Another critical enabling technology for next-generation laser altimetry and surface/biomass mapping from space is high-sensitivity low-noise avalanche photodiode (APD) 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 GHz bandwidth. We are currently working with various vendors to develop high bandwidth multi-element photon-counting analog detectors during the first two years of the program. Candidate detectors for our IIP prototype instrument include HgCdTe on CdZnTe APDs, impact-ionization-engineered InAlAs APDs [2] and multi-element anode InGaAsP intensified photodiode detectors (IPD).[3]

4.3. OPTICAL SYSTEM

The airborne demonstrator will consist of sixteen beams orient in a 4x4 grid pattern with uniform spacing between spots. The overall dimension of the grid is 75 m x 75 m (7.5 mrad x 7.5 mrad) with 20 m (2mrad) between spots. The grid will have a 14.5°±1° clocking with respect to the aircraft velocity vector to yield an effective 5m spot cross-track spacing as shown in **Figure 4.** A diffractive optical element (DOE) will be used to divide a single beam into 16 beams necessary for the demonstration. Similar DOE is being used presently on the Lunar Orbiter Laser Altimeter (LOLA) instrument on the Lunar Reconnaissance Orbiter (LRO). [4]

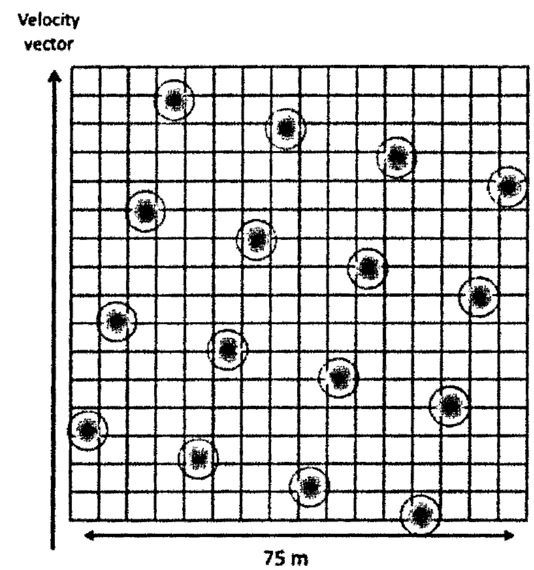

Figure 4. This figure illustrates the baseline footprint configuration of the IIP airborne instrument from 10 km altitude. The solid circles are the 5 m laser footprints with the open circles showing the detector field of view of 7 m.

4.4. AIRBORNE DEMONSTRATION

In Year 3 (2011) of this IIP, we plan to perform airborne testing of the swath-mapping concept with technologies developed during Year 1 and 2. We will leverage our recent experience on a micropulse lidar airplane demonstration.[5] Our past demonstration had a 1 μJ (per beam) pulse-energy high-repetition-rate laser and a single-photon-threshold (only) detector (Geiger-mode APD) based receiver. In contrast, our new instrument will demonstrate a 100 μJ (per beam) pulse-energy high-repetition-rate laser and a single-photon-sensitive analog-mode detector waveform-digitized based receiver. The current plan is to operate the instrument at an altitude of 40000 ft or approximately 12 km. We intend to scale the receive telescope on this airborne experiment to the LIST mission concept. The proposed mission concept for LIST is to orbit at 400 km with a receive telescope of diameter of 2-m. With the airplane at altitude of 12 km, a receive telescope of approximately 2.4 inch diameter will provide the correct scaling for space operation. A total of twenty to twenty-five flight tests are being considered for this IIP. Candidate geographic region for the field tests will be selected to demonstrate measurement concept that fully satisfy the LIST science objectives of mapping in cryosphere, water cycle, vegetation structure and solid Earth.

Table 1 shows a comparison between the airborne instrument being developed under this IIP and the LIST spaceborne instrument requirements.

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

[illegible]	[illegible]	[illegible]	[illegible]
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 µJ per beam for 1000 beam @ 10 kHz – 1 kW optical power or 6.7kW prime power assuming 15% efficiency	100 µJ 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 35th 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

We are developing technologies and showing the path toward maturing technologies necessary to meet the LIST mission requirements under the current IIP effort. Technologies developed during the first two year will be incorporated in a Year 3 airborne instrument simulator with the objectives to mitigate risks and developing measurement technique for future analog waveform lidar mission.

6. ACKNOWLEDGMENT

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