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

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I. ABSTRACT

In 2007, the National Research Council (NRC) completed its first decadal survey for Earth science at the request of NASA, NOAA, and USGS. 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 within a few years. 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 altimeter.

II. INTRODUCTION

The objective of our work is to demonstrate key capabilities of a new, highly efficient laser altimeter for the LIST mission. The LIST instrument needs to be able to generate a swath with 5 m pixels 5 km wide, image this swath onto a detector array and produce a range image with the topographic height of the sampled area. This includes measuring through foliage if covered by vegetation, and measuring the 3-D structure of the vegetation cover. Our swath mapping approach uses a 5 km wide swath composed of 1000 laser beams in a linear array and 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. The spots are contiguous cross-track. At 10 kHz laser pulse rate and a nominal spacecraft ground velocity of 7 km/sec, laser footprints are spaced 0.7 m along track yielding 7 illuminating laser pulses per 5 m pixel. This over-sampling along track allows detecting ground echo pulses under realistic observing conditions, such as attenuation from thin clouds and ground obscuration by vegetation.

Our basic approach is flexible and scalable in swath width, pixel width, laser power and telescope size. For the laser, we have been developing a high-efficiency high-repetition-rate master oscillator power amplifier laser transmitter, using a diffractive optical element after the laser to produce multiple beams. The laser backscatter from the surface is collected with a diffraction-limited telescope and the spots from the swath are imaged onto a sensitive detector array. We are currently developing a high-sensitivity, low-noise avalanche photodiode (APD) detector array that operates in a quasi-analog mode.

Our development activity is in the second year of a three-year NASA ESTO IIP program. During Year 3 we plan to perform airborne testing of the swath-mapping concept. Candidate geographic regions for the field tests have been selected to demonstrate measurements that satisfy the LIST science objectives for topographic mapping in the focus areas of cryosphere, water cycle, and vegetation structure. In this paper we will summarize some of the instrument characteristics and approaches we are using to reduce risks for LIST based on the airborne instrument development and its demonstration measurements.

III. 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.

IV. 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.

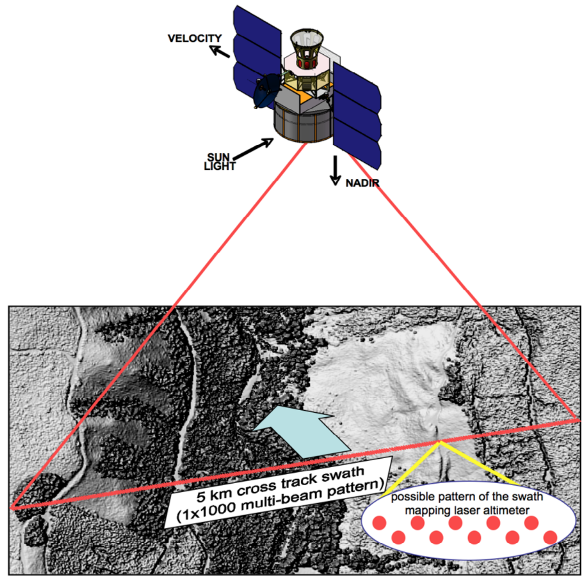

Figure 1. Concept drawing of the LIST satellite generating a 5 km swath containing 1000 beam spots at 5 m per spot.

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.

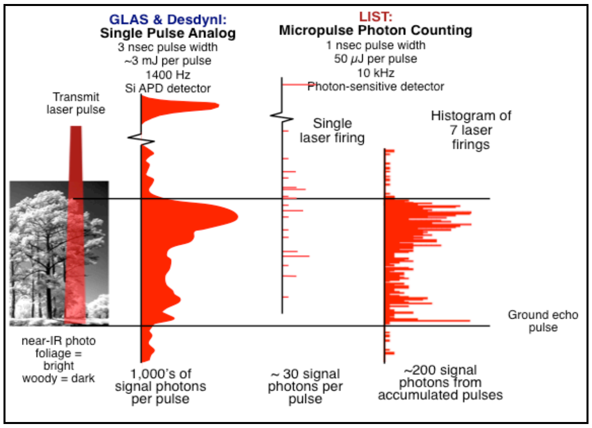

Figure 2. Approaches for measuring the time-of-flight information of laser echo pulses into vegetation structure heights and ground return.

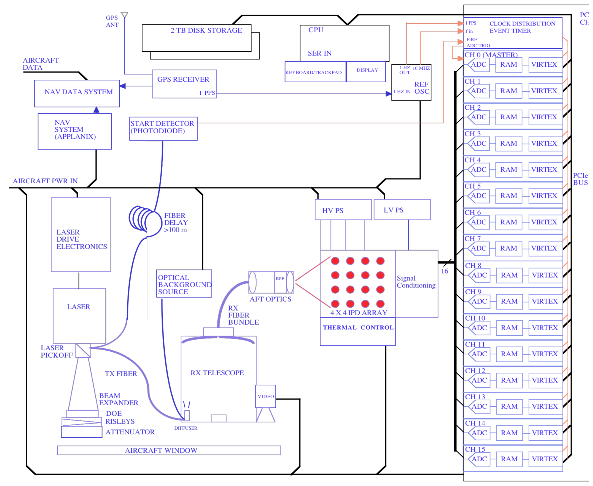

Figure 3. Functional block diagram of the airborne IIP instrument.

V. 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.

A. INSTRUMENT

The airborne instrument under development for this IIP is shown schematically in **Figure 3**. The laser transmitter output is split and a small part of the outgoing beam will be sent to the receive telescope for illuminating the detector array. This is the start pulse for that particular measurement. The remaining majority signal will be divided into 16 beam oriented in a 4x4 grid. The return echo signal will be coupled into a fiber bundle and imaged onto the detector array. The output of the linear mode photon counting array will be digitized using a commercial –off-the-shelf (COTS) 16-channel digitizer with 1.5 GSamples/sec and 8-bit resolution.

B. LASER TRANSMITTER

For LIST a swath of 5 km can be generated using 1000 beams each having 5 m footprint. Our goal for 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. Using 10 MOPA lasers, each subdivided to generate 100 beams, would produce the needed 1000 beam swath. Thus each MOPA laser will need to deliver an energy of >10 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.

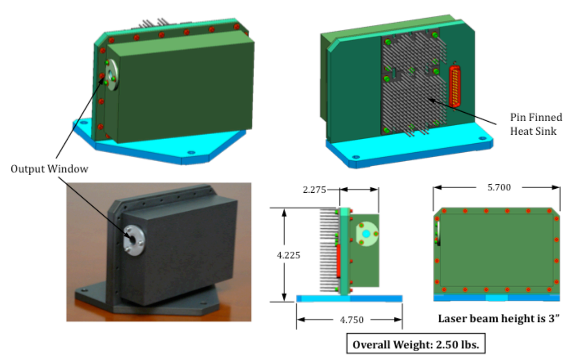

Figure 4. Master oscillator delivered by RSAS for the laser altimetry instrument.

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. The master oscillator (MO), developed by Raytheon Space and Airborne Systems (RSAS) is a diode pumped Yb:YAG microchip laser (see **Figure 4**). This is used to seed a power amplifier (PA) stage that is based on a planar waveguide amplifier design championed by RSAS.

C. DETECTOR AND DATA SYSTEM

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 currently developing a high bandwidth multi-element photon-sensitive detector array with Intevac (see **Figure 5**). The 4x4 InGaAsP multi-element anode intensified photodiode (IPD) array will have >20% quantum efficiency (QE) at 1 μm wavelength, dark count of <0.5 MCounts/second/pixel and gain of >10,000. [2] The output of this array will be sent to a commercial off-the-shelf (COTS) 16-channel, 1.5 GSamples/s digitizer. As part of this IIP, we are also performing a trade study on potential detectors that are candidates for this application. Candidate detectors for our prototype lidar include HgCdTe on CdZnTe APDs, impact-ionization-engineered InAlAs APDs [3].

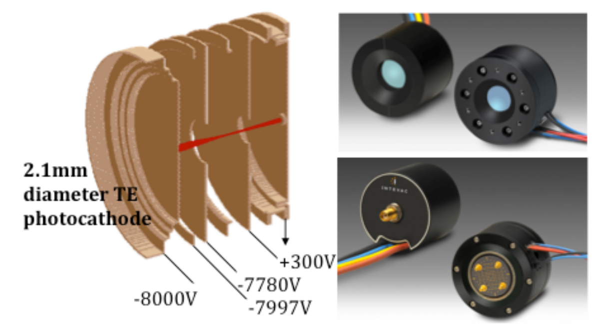

Figure 5. 4X4 InGaAsP IPDs developed by Intevac will be used in this IIP.

The digitizer output will be fed into a flight computer. The flight computer manages the data flow from both the digitizer and navigation sensor with appropriate time stamps and stores them at a sustainable rate of about 500 MB/s. Flight software for both airborne and ground systems are also being developed. The airborne software will provide digitizer initialization, acquire data from each of the sixteen channels, perform aliveness tests, display limited real-time in-flight data, and write the data to removable hard drives. The airborne software will also collect and store navigation and housekeeping data. Upon completion of a flight test, the hard drives will be moved to an identical ground station computer system. The ground computer system will back up the data and generate science data products.

D. OPTICAL SYSTEM

The airborne lidar will demonstrate a 16-beam version of the LIST space lidar. The 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 6**. 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].

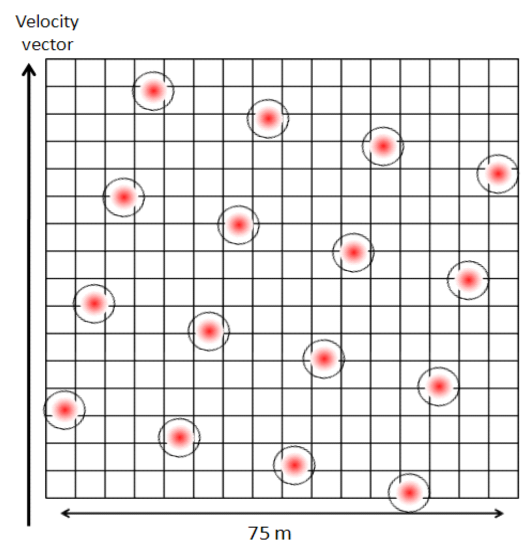

Figure 6. This figure illustrates the baseline footprint configuration of the IIP airborne lidar from 10 km altitude. The solid circles are the 5 m laser footprints with the open circles showing the detector field of view of ~7 m.

E. 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 μJ 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 µJ 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.

Table 1. Comparison of space- and airborne 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 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

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.

VI. CONCLUSIONS

With 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.

VII. ACKNOWLEDGMENT

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